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July
2019

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Cover design: Rob Hudgins

CHEMICAL ENGINEERING
ESSENTIALS FOR THE CPI PROFESSIONAL

Editor's Page

2019 Nicholas Chopey Scholarship

Chemical Engineering established the annual Chopey Scholarship for Chemical Engineering Excellence in late 2007 to bring recognition to the chemical engineering profession and to help advance that profession. The award is named after Nicholas P. Chopey, the magazine's former Editor-in-Chief who contributed greatly to *CE* for over 47 years of his professional career. The scholarship is awarded to third-year students who are pursuing an undergraduate course of study in chemical engineering.

The award winner

Jacob Klenke

Congratulations to this year's scholarship winner, Jacob Klenke, who will be entering his senior year in the chemical engineering curriculum at the University of Oklahoma (www.ou.edu). He is also pursuing minors in computer science and mathematics, and has done research in protein separation techniques with the department of chemistry. In addition, Klenke serves as a teaching assistant for sophomore-level chemical engineering courses. He is currently spending the summer as an EPDM (ethylene propylene diene terpolymer) process engineering intern with Carlisle Construction Materials.

Klenke says that a high school passion for chemistry and an interest in solving technological problems led him to choose to follow a chemical engineering curriculum. Learning about the wide variety of ways that chemical engineers can effectively apply their skills and the impact that they make, attracted him to stay in the field. He plans to pursue an M.S. degree at the University of Oklahoma and then move into industry as a process engineer.

In addition to his academic pursuits, Klenke also enjoys playing the tuba, moderating a reading group and hiking the state parks of Oklahoma.

About the scholarship

The scholarship is awarded to current third-year students who are enrolled in a fulltime undergraduate course of study in chemical engineering at one of the following four-year colleges or universities, which include Chopey's alma mater and those of our editorial staff: University of Buffalo, University of Kansas, Columbia University, University of Virginia, Rutgers University and the University of Oklahoma.

The selection program utilizes standard Scholarship America recipient procedures, including the consideration of past academic performance and future potential, leadership and participation in school and community activities, work experience, and statement of career and educational goals. The scholarship is a one-time award.

More information about the award, including how to apply and how to donate to the scholarship program, can be found on our website at www.chemengonline.com/npcscholarship.

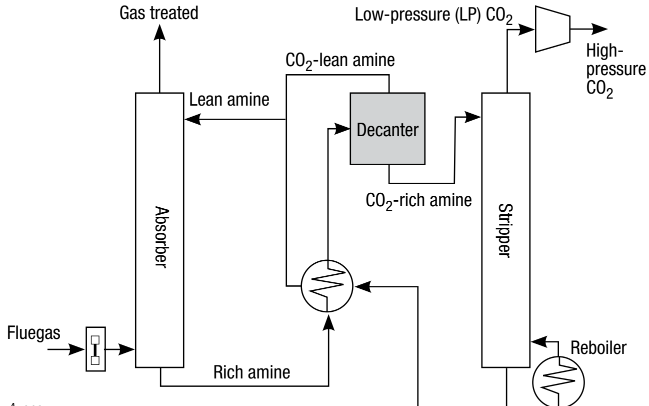
In this issue

This month's cover story focuses on a topic that is of great concern to many in the chemical process industries (CPI) — a potential shortage of technical talent and experience — and offers suggestions on how to improve the situation. This issue also contains articles on methane reforming, water treatment for cooling towers, intermediate bulk containers, particle size characterization and much more. We hope you enjoy reading. ■

Dorothy Lozowski, Editorial Director

European project aims to develop CCS technology on an industrial scale

Last month, a consortium of 11 European partners, including ArcelorMittal, Axens, IFP Energies nouvelles (IFPEN) and Total, launched a project to demonstrate an innovative process called DMX for capturing CO_2 from industrial activities. It is part of a more comprehensive study dedicated to the development of the future European Dunkirk North Sea Capture and Storage Cluster.



Axens

The 3D project (DMX Demonstration in Dunkirk) is part of Horizon 2020, the E.U's research and innovation program. The four-year, €19.3-million project is coordinated by IFPEN, and has three main objectives: 1) to demonstrate the effectiveness of the DMX process on a pilot scale; 2) prepare the implementation of a first industrial unit at the ArcelorMittal site in Dunkirk, which could be operational starting in 2025, capturing 1 million metric tons per year (m.t./yr) of CO_2; 3) design the future European Dunkirk North Sea Cluster, which should be able to capture, pack, transport and store 10 million m.t./yr of CO_2 and should be operational by 2035.

The pilot, designed by Axens (Rueil-Malmaison, France; www.axens.net), will be built starting in 2020 at the ArcelorMittal steelworks site in Dunkirk and will be able to capture 0.5 m.t./h of CO_2 from steelmaking gases by 2021. It will use the patented DMX process, which stems from IFPEN's Research and will be licensed by Axens.

The DMX process (flowsheet) is based on a specific amine solvent that separates into two liquid phases for specific CO_2 loadings or temperature condition: one having a high CO_2 loading. Separating the two phases in a decanter makes it possible to reduce the mass of solvent that has to be regenerated. This reduces the energy consumption for capture by nearly 35% compared to conventional monoethylamine (MEA) reference process. Additionally, using the heat produced on site will cut capture costs in half, to less than €30/m.t. of CO_2, says Axens.

A sound way to make MOFs

Researchers from RMIT University (Melbourne, Australia; www.rmit.edu.au) have demonstrated a "green" technique that can produce customized metal organic framework (MOF) compounds in minutes, harnessing the power of high-frequency (ultrasonic) sound waves.

MOFs are extremely versatile materials that can be used to sense and trap substances at minute concentrations, to purify water or air, and can also store large amounts of energy. However, the traditional way of creating them is environmentally unsustainable and can take several hours or even days. During the standard production process, solvents and other contaminants become trapped in the MOFs' holes. To flush them out, researchers use a combination of vacuum and high temperatures, or chemical solvents that can be harmful, in a process called "activation".

In their new technique, RMIT researchers use a microchip to produce high-frequency sound waves. The researchers said: "At the nanoscale, sound waves are powerful tools for the meticulous ordering and maneuvering of atoms and molecules. The components of a MOF — a metal precursor and a binding organic molecule — are exposed to sound waves. The sound waves allow creating a highly ordered and porous network, while at the same time "activating" the MOF by pushing out the solvents from the holes, according to the researchers. Lead investigator Leslie Yeo, professor of chemical engineering and director of the Micro/Nanophysics Research Laboratory at RMIT, says the new method produces MOFs with empty holes and a high surface area, eliminating the need for post-synthesis activation.

The researchers successfully tested the technique on copper and iron-based MOFs. The technique can be expanded to other types of MOFs.

Edited by:
Gerald Ondrey

PDH CATALYST

Last month, Clariant's Catalyst business (Munich, Germany; www.clariant.com) launched its latest propane dehydrogenation (PDH) catalyst, Catofin 311, which is said to deliver greater selectivity and a longer lifetime than its predecessors, resulting in increased overall profitability for propylene producers. Catofin 311 further enhances the proven benefits of previous generations through improvements in selectivity and longevity. For a typical 600,000-ton/yr PDH unit, users could benefit from increased productivity of up to $20 million over the lifetime of the Catofin 311 catalyst, says the company.

ANILINE-FREE INDIGO

Last month, Archroma (Reinach, Switzerland; www.archroma.com) announced that Vietnam-based Tuong Long Co. Ltd (www.tuonglong.com) is the first denim manufacturer in Vietnam to switch 100% of its production to Archroma's aniline-free Denisol Pure Indigo dye.

First launched in May 2018, Denisol Pure Indigo 30 liquid dye is a non-toxic way to produce the traditional, iconic indigo blue that consumers associate with denim and jeans. During production, some of the aniline stays locked into the indigo pigment and is difficult to wash off the fabric. The remainder of the aniline impurity, approximately 300 m.t./yr, is discharged during dyeing. This can be an issue because aniline is toxic to aquatic life. In addition, exposure levels to factory workers can be high. As a result of its toxicity (more hazardous than alkylphenols), it is now starting to feature on the restricted substance lists (RSL) of some major clothing brands and other retailers.

Tuong Long's textile plant is

(Continues on p. 8)

located near Ho Chi Minh City and employs 600 people producing up to 18,000,000 m/yr of fabric.

ROSE WATER

A team led by associate professor Donglei Fan in the Cockrell School of Engineering's Walker Dept. of Mechanical Engineering at the University of Texas at Austin (www.utexas.edu) developed a new approach to solar steaming for water production — a technique that uses energy from sunlight to separate salt and other impurities from water through evaporation. An origami rose provided the inspiration for developing the new kind of solar-steaming system made from layered, black paper sheets shaped into petals. The black paper is coated with polypyrrole, a material known for its photothermal properties (converting solar light into heat). Attached to a stem-like tube that collects untreated water from any water source, the 3-D rose shape makes it easier for the structure to collect and retain more liquid. Current solar-steaming technologies are usually expensive, bulky and produce limited results. The rose-inspired method uses inexpensive materials that are portable and lighweight. ❑

Removing PFAS from wastewater

A new low-cost, safe and environmentally friendly method for removing polyfluorinated alkyl substances (PFAS) from water has been developed by researchers from Flinders University (Adelaide, Australia; www.flinders.edu.au).

PFAS are commonly used in non-stick and protective coatings, lubricants and aviation fire-fighting foams, and have also been seen as a health hazard. The researchers at Flinders University have developed an absorbent polymer, made from waste cooking oil and sulfur combined with powdered activated carbon. The polymer adheres to carbon in a way that prevents caking during water filtration. It works faster than the commonly used granular activated carbon and it lowers the amount of dust generated by handling powdered activated carbon, lowering respiratory health risks faced by clean-up workers.

During the testing phase, the research team was able to observe the self-assembly of hemi-micelles on the surface of the polymer. The team demonstrated the effectiveness of the polymer-carbon blend by purifying a sample of surface water obtained near a Royal Australian Air Force airbase. The new filter material reduced the PFAS content of this water from 150 parts per trillion (ppt) to less than 23 ppt — well below the 70 ppt guidance value for PFAS limits in drinking water of the Australian Government Dept. of Health.

One of the researchers associated with the development of the new polymer, Justin Chalker, says: "The next stage for us is to test this sorbent on a commercial scale and demonstrate its ability to purify thousands of liters of water. We are also investigating methods for recycling the sorbent and destroying the PFAS."

Self-healing elastomers from waste lignin

Lignin — a component making up 25–35% of woody biomass — is underutilized as a byproduct of biofuels production and paper-making processes. Because of its abundance, low-cost and sustainability, lignin is being investigated as a raw material for making higher-value chemicals. Researchers at Oak Ridge National Laboratory (ORNL; Oak Ridge, Tenn.; www.ornl.gov) have developed a stretchy material from waste lignin that exhibits self-healing behavior and could be used in adhesives and other industrial applications.

Scientists led by Amit Naskar extracted an oligomer from lignin with acetonitrile using an extraction method that concentrates the regions of lignin that contain carboxylic acid functional groups. The material is a uniform lignin oligomer with a high degree of carboxylic acid functionalization and a high glass-transition temperature (T_g). Then the team reacted the lignin oligomer with polyethylene glycol (PEG), forming an elastomeric material with a network of both covalent bonds and hydrogen bonds.

"This network contains both stiff phases, from the lignin, and soft phases, from the PEG," explains Naskar. The resulting material is highly elastic, with the ability to stretch by over 2,000%, as well as very tough, Naskar says. In addition, the plentiful hydrogen bonds give the material the ability to self-heal if cut.

The new ORNL material is being investigated for a range of industrial applications, such as coatings, glues and hydrogels, where it is a possible bio-based replacement for dihydroxyphenylacetic acid, the derivative compound of dopamine that is responsible for the strong adhesion of mussels.

Iodine-oxidizing bacteria could leach gold underground

Gold is usually leached from ore using hazardous substances, such as cyanide, mercury, aqua regia and others. Although there has been some progress in developing bioleaching technology, such methods still require mining and processing the ore before micro-organisms can go to work. Now, Yuichi Sugai and colleagues at Kyushu University (http://reps.mine.kyushu-u.ac.jp/reps) have demonstrated the ability to leach gold directly from ore — without mining operations — using bacteria isolated from a natural gas field.

The underground brine water in natural gas fields in Japan contains high concentrations of iodide (120 parts per million, or 2,000 times higher than the concentration in seawater), as well as iodide-oxidizing bacteria (IOB), which oxidize I^- into iodine (I_2). Because gold can be dissolved in I^-/I_2 mixture, Sugai came up with the idea to use the IOB for gold leaching. Eight strains of IOB were isolated from a natural gas field and incubated in the culture medium containing nutrients, iodide and gold ore (gold grade: 0.26 wt.%, pulp density: 3.3 wt./vol.%) at 30ºC. The strains oxidized I^- into I_2 to generate triiodide, $(I_3)^-$, which releases gold from the ore into solution as gold diiodide, $(AuI_2)^-$. Three IOB strains successfully dissolved gold from ore completely within 30 days — the best within 5 days. This proof-of-concept demonstrates the possibility for in situ gold leaching, which has the potential to be more economical and environmentally sustainable than traditional techniques. "IOB are bad bacteria in the gas field, because they cause corrosion of wells and pipes," says Sugai, but adds that "they can become good" because of this special ability.

The study was funded by a university grant, and the results published in the May 2 issue of *Minerals*.

Insight into the mechanism for enzymatic biofuel production

Enzymes that are responsible for the production of hydrocarbons in blue-green algae — a hydrocarbon producing cyanobacteria — have now been identified by the research group of Munehito Arai at The University of Tokyo (Japan; www.c.u-tokyo.ac.jp). Along with this achievement, the researchers discovered the important amino acids within the enzymes that enable the enzymes to work efficiently, and believe the breakthrough can be applied for the efficient production of renewable biodiesel fuels.

The researchers compared the amino-acid sequences and the hydrocarbon-producing activities of ten representative aldehyde-deformylating oxygenases (ADOs), which catalyze a difficult and unusual reaction in the conversion of aldehydes to hydrocarbons — a technique that has been widely used for biofuel production in metabolic engineering. The activity was found to be highest for the ADO from *Synechococcus elongatus* PCC 7942 (7942ADO). In contrast, the ADO from *Gloeobacter violaceus* PCC 7421 (7421ADO) had low activity but yielded high amounts of soluble protein, resulting in a high production level of hydrocarbons. By introducing 37 single amino acid substitutions at the non-conserved residues of the less active ADO (7421ADO) to make its sequence more similar to that of the highly active ADO (7942ADO), they found 20 mutations that improved the activity of 7421ADO. In addition, 13 other mutations increased the amount of soluble ADO while maintaining more than 80% of wild-type activity. Correlation analysis showed a solubility-activity trade-off in ADO, in which activity was negatively correlated with solubility.

Selectively perform cross-coupling reactions with this catalyst

Twofold C–H activation and cross-coupling of stoichiometric amounts of organic molecules, R_1–H and R_2–H, to form an R_1–R_2 product that is free of homocoupling products (R_1–R_1 or R_2–R_2) is a goal to simplify organic synthesis of certain compounds. Up to now, the only reliable strategy to eliminate the homocoupling side products effectively is to use an excess of one reactant over another.

Now, professor Eiichi Nakamura and colleagues at the University of Tokyo (www.u-tokyo.ac.jp) have succeeded in performing a one-step conversion of stable C–H bonds into C–C bonds at mild conditions with 100% selectivity. For the first time, the researchers have discovered a simple and highly efficient way to produce certain kinds of organic compounds. The reported new method — which uses a novel iron catalyst — can not only simplify organic synthesis, but would greatly reduce costs and cut down on waste products, which could have huge implications for industrial production of pharmaceuticals, petrochemicals and more.

The method uses an N-(quinolin-8-yl)amide anion for a temporary connection, followed by the cross-coupling of a stoichiometric mixture of aromatic compounds. The reaction takes place under mildly oxidative, iron-catalyzed conditions, through the formation of a heteroleptic R_1–M–R_2 intermediate, and has a high yield without any trace of homocoupling products.

"I felt drawn to investigate the use of iron as a catalyst to speed up reactions," says Nakamura. "It's intriguing how on one hand it's cheap, abundant and nontoxic, but on the other hand it's difficult to control iron's catalytic ability due to its complex electronic behavior." Nakamura and colleagues were able to fine-tune a first-of-its-kind iron catalyst so that it selects which C–H bonds to combine and which bond pairings to reject.

Smart retrosynthesis simplifies reaction design

A new retrosynthesis platform enables users to work backwards from a target molecule to optimize synthesis pathways. MilliporeSigma's (Burlington, Mass.; www.sigmaaldrich.com) Synthia software uses sophisticated algorithms backed by a database of over 72,000 coded reaction rules to provide precise pathways to novel and known organic molecules of interest, explains Sarah Trice, director and head of MilliporeSigma's Cheminformatics Technologies business unit. After 15 years of academic development, MilliporeSigma launched Synthia commercially in April 2019. Synthia is said to be the first commercial platform of its kind on the market. "Of the other retrosynthesis tools we have seen, we are highly differentiated. Most other softwares use machine learning to analyze publically available databases, but there are inherent problems with this approach. The data sets are not clean, and a massive amount of data must be included. The resulting pathways do not consider a holistic view of the entire molecule. Given our hand-coding approach, our platform considers reactions that may have only been performed a handful of times, which is hard to do with a machine-learning approach," says Trice. Furthermore, Synthia is highly tunable, taking into account not only complex parameters, such as stereochemistry, but also feedstock considerations. "If someone is interested in only using commodity chemicals as starting materials, they can put input price constraints for commercially available feedstocks, and the software will only look at pathways using those starting materials," adds Trice.

In internal experiments, Synthia evaluated new pathways for eight chemicals manufactured by MilliporeSigma, each of which suffered from low yields, overly difficult pathways, or high risks. All of the resulting pathways were deemed valid in laboratory tests, and for one product, the company was able to quickly commercialize a simpler, higher-yield route and realize significant profit increases. Currently, the development team is expanding the rules database, enhancing the search capabilities, and fine-tuning the prediction of reaction conditions using machine learning and artificial intelligence.

Thyssenkrupp introduces artificial intelligence ‘alfred’

Thyssenkrupp Materials Services GmbH (Essen, Germany; www.thyssenkrupp-materials-services.com) continues to drive digital transformation. Since early 2019, an artificial intelligence (AI) solution, supported by Microsoft’s cloud platform Azure, has been integrated into the processes of the largest materials distribution and service provider in the Western world. Dubbed “alfred” after his namesake Alfred Krupp, the AI solution supports his colleagues at Materials Services in dynamically managing the global logistics network with 271 warehouse sites and more than 150,000 products and services.

As a first step, alfred will help to optimize transport routes and thus save the transport of thousands of tons of material per year. In addition, materials will be available more quickly at the right locations in the future. In the medium term, Materials Services will be able to make all processes along the supply chain more flexible, for example, in order to better take into account specific customer requirements for delivery speed, pricing or material quality.

With the AI, the approximately 14-million order items received annually by Materials Services can be processed and analyzed much more efficiently. For the first time, the materials experts are also bringing all company data together on a single platform. Using self-learning algorithms based on Microsoft Azure Machine Learning, alfred analyzes all relevant information, generates important findings and supports employees with appropriate recommendations.

Sound solutions to low frequency noise

Low-frequency noise (≤500 Hz) from various sources, such as construction machinery and aircrafts, is a form of noise pollution that transmits over long distances and disturbs the surrounding area. It is also known to trigger several negative physiological reactions, such as changes to blood pressure, vertigo and breathing difficulties, even when the noise is not audible. Currently, most commercially available noise-cancelling devices and structures are only effective in reducing high-frequency noise, while low-frequency noise continues to penetrate. Therefore, to more effectively mitigate low-frequency noise, a team of mechanical engineers from the National University of Singapore (NUS; www.nus.edu.sg) has designed a set of effective noise-attenuating blocks.

Described in a recent issue of *Acoustics*, the 3-D printed blocks can be customized to cancel a specific noise frequency by adjusting the size of the air cavity and the neck opening within the block. The blocks can then be slotted into a grid-like host structure to function as a noise barrier. Laboratory studies showed that the modular design was capable of canceling low-frequency noise below 500 Hz by an average of 31 dB. This is said to be six times more effective than other commonly used noise barriers, and the barrier is lighter and thinner than commercially available devices. Using this modular design, the NUS engineers are able to better control the properties of the noise barrier and produce them affordably.

“These noise-reduction blocks can be easily incorporated as part of existing wall structures, and it would not be necessary to build a host structure from scratch in order to implement the sound barrier,” explains NUS Mechanical Engineering associate professor Lee Heow Pueh. “Such a modular design also means that a variety of blocks targeting different noise frequencies can be used within the same host structure to effectively block a range of low-frequency noise.”

The team also developed Noise Explorer, a mobile application capable of accurately tracking noise data based on a new method of calibrating the microphones of smartphones.

Magnetism gives water splitting a big boost

In a paper published last month in *Nature Energy*, scientists from the Institute of Chemical Research of Catalonie (ICIQ; Tarragona, Spain; www.iciq.org) describe how, for the first time, a magnet has been used to directly enhance the production of hydrogen in alkaline water electrolyzers. “The simplicity of the discovery opens new opportunities to implement magnetic enhancement in water splitting,” says Felipe A. Garcés-Pineda, first author of the paper. “Furthermore, the low cost of the technology makes it suitable for industrial applications,” he says.

The research shows how the presence of an external magnetic field — induced by approaching a neodymium magnet to the electrolyzer — spurs the electrocatalytic activity on the anode, in some cases, increasing the H_2 production two-fold. The scientists report that the magnetic field directly affects the reaction pathway by allowing for spin conservation of the active catalyst, which in turn favors parallel spin alignment of the oxygen atoms during the reaction. This overall spin polarization, due to the external magnetic field, improves the efficiency of the process. “This demonstrates that there is a lot to learn from the intimate reaction mechanisms taking place on electrocatalysts and opens new ways to overcome the limitations of state-of-the-art systems,” says Núria López, ICIQ group leader and co-author of the article.

The researchers studied a variety of catalysts in identical working conditions and report the catalytic activity enhancement is proportional to the magnetic nature of the catalysts used to drive the water-splitting reaction. $NiZnFe_4O_x$, a highly magnetic ferrite, exhibited the biggest enhancing effect when presented with a magnetic field. This ferrite also possesses the advantage of being able to magnetically attach itself to a nickel metal support — curbing the need to use binders to attach catalysts to a physical support. ■

Business News

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Plant Watch

Bilfinger wins €60-million contract from SABIC

May 23, 2019 — Bilfinger SE (Mannheim, Germany www.bilfinger.com) has been chosen as maintenance partner for a €60-million contract by SABIC UK Petrochemicals Ltd. to carry out a range of services across facilities on its Teesside, U.K. site. The services will include mechanical, electrical and instrumentation engineering, as well as access, insulation, painting, and asbestos management and removal. The four-year contract has a volume of circa £50 million (€57.8 million).

BASF to build two plants at its new Verbund site in Zhanjiang

May 21, 2019 — BASF SE (Ludwigshafen, Germany; www.basf.com) plans to build an engineering plastics compounding plant and a thermoplastic polyurethane (TPU) plant at the company's proposed integrated chemical production ("Verbund") site in Zhanjiang, China. These will be the first production plants to come onstream at the site. By 2022, the new engineering-plastics compounding plant will supply an additional capacity of 60,000 metric tons per year (m.t./yr) of BASF engineering plastics compounds in China. This will bring the total BASF capacity of these products in Asia Pacific to 290,000 m.t./yr.

Hyundai Chemical selects Unipol PE technology for new HDPE plant

May 20, 2019 — Hyundai Chemical Company, Ltd. (Daesan, South Korea; www.hyundaicorp.com) has chosen Univation Technologies' (Houston; www.univation.com) Unipol PE technology for a 300,000-ton/yr high-density polyethylene (HDPE) plant to be located at Hyundai's site in Daesan, Republic of Korea. Hyundai will utilize a broad range of Univation's HDPE product technology portfolio.

Opening ceremony for new chemical complex in Louisiana

May 16, 2019 — Lotte Chemical USA (Lake Charles, La.; www.lottechem.com) and Westlake Chemical Corp. (Houston; www.westlake.com) hosted an official opening ceremony on May 9, 2019, for their joint-venture ethylene plant and the Lotte Chemical world-scale ethylene glycol (EG) production facility near Lake Charles, Louisiana. The complex is a $3.1-billion project, which broke ground in June 2016, and will include an ethane-cracker plant, a joint venture between Lotte Chemical and Westlake Chemical, and the ethylene glycol plant. The combined site covers approximately 250 acres.

Thyssenkrupp to build a new fertilizer plant in Poland

May 16, 2019 — Thyssenkrupp's Industrial Solutions business area (Essen, Germany; www.thyssenkrupp-industrial-solutions.com) has received a new order for the construction of a fertilizer plant in Poland. The customer for the project is ANWIL, a subsidiary of PKN ORLEN, one of the largest oil industry corporations in Central and Eastern Europe from Poland. The new facilities for the production of 1,265 m.t./d of nitric acid and 1,200 m.t./d of ammonium nitrate will be located in Wloclawek, some 200 km northwest of Warsaw, at an existing chemical and fertilizer complex. Thyssenkrupp's patented EnviNOx process will be used to remove greenhouse gases from nitric acid production.

ExxonMobil doubles capacity of specialty elastomers at Wales plant

May 14, 2019 — ExxonMobil (Irving, Texas; www.exxonmobil.com) has completed an expansion of its specialty elastomers manufacturing plant in Newport, Wales, which doubles the plant's manufacturing capacity and increases global manufacturing capacity of Santoprene thermoplastic elastomers by 25%. Santoprene thermoplastic elastomers are engineered to perform like vulcanized rubber, and can be re-used and re-engineered, leading to reduced shipping weights and improved recycling capabilities.

Oxea increases production capacity for isononanoic acid

May 14, 2019 — Oxea (Monheim am Rhein, Germany; www.oxea-chemicals.com) successfully completed a debottleneck of its existing isononanoic acid production units in Oberhausen, Germany. The company will use the additional production capacity to support the growth of the global synthetic lubricants market. This debottlenecking project is the first in a series of improvements designed to increase Oxea's production capacity for carboxylic acids in the short term. The company also aims to bring its sixth world-scale carboxylic acids production plant on stream in 2021.

Mergers & Acquisitions

Air Liquide China to divest its dedicated gases complex

June 11, 2019 — Air Liquide China (Shanghai; www.airliquide.com/china) has entered

into an agreement to sell to its client Fujian Shenyuan New Materials Co. Ltd., its subsidiary Air Liquide Fuzhou Co. Ltd. which owns and operates the integrated gas complex in Fujian (Southeast China). The industrial gases complex sold includes a coal-gasification unit in addition to an air separation unit, a synthetic-gas-purification unit and an ammonia plant.

Genomatica acquires assets from REG Life Sciences

June 6, 2019 — Genomatica (San Diego, Calif.; www.genomatica.com) has acquired certain assets of the REG Life Sciences division (REG LS) of Renewable Energy Group, Inc., the largest supplier of advanced biofuels in North America. Genomatica intends to use these assets to develop a wider range of sustainable chemicals, which in turn are used to make numerous everyday materials and products.

DSM expands in India with specialty-materials acquisition

May 13, 2019 — Royal DSM (Heerlen, the Netherlands: www.dsm.com) has reached an agreement with SRF Ltd., to acquire its Engineering Plastics business, a leading player in India in the development, production and sale of specialty materials. The acquisition is expected to close in Q3 2019, subject to customary closing conditions. SRF's Engineering Plastics business, founded in 1979, with its main operations located in Pantnagar, India, realized sales of about $37 million in 2018 and has seen double-digit growth in recent years.

Umicore to acquire Co-refinery and operations in Finland

May 24, 2019 — Umicore N.V. (Brussels, Belgium; www.umicore.com) has reached an agreement to acquire Freeport Cobalt's cobalt-refining and cathode-precursor activities in Kokkola, Finland, for a total consideration of $150 million on a debt- and cash-free basis, plus the value of the working capital to be taken over at closing, which at the end of March was approximately $40 million. The transaction, which is subject to customary closing conditions, including regulatory approvals, and is expected to be finalized by the end of 2019. Umicore is not acquiring the cobalt fine powders, chemicals, catalysts, ceramics and pigments activities located on the same site. These activities will continue to be run by Freeport Cobalt.

TASI Group acquires Sierra Instruments

May 15, 2019 — The TASI Group (Harrison, Ohio; www.tasigroup.com) continues the growth of its Flow Segment business with the recent acquisition of Sierra Instruments Inc. (Monterey, Calif.; www.sierrainstruments.com), a global company specializing in the manufacture of flow measurement instrumentation. This is the second acquisition finalized by The TASI Group in just two months. ■

Gerald Ondrey

Making the Most of Methane Reforming

Despite valiant quests to find sustainable routes to syngas, methane reforming continues to play the lead — and 'greener' — role

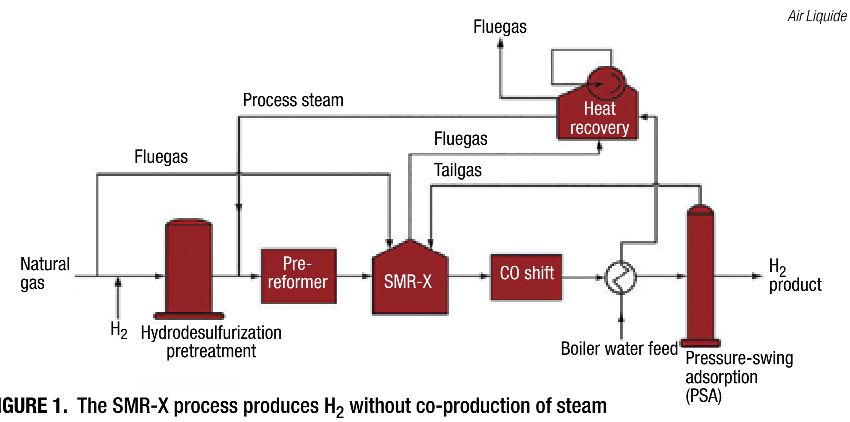

FIGURE 1. The SMR-X process produces H_2 without co-production of steam

For decades, the production of synthesis gas (syngas, H_2 + CO) from fossil-based feedstocks has been the key process for many sectors in the chemical process industries (CPI). Although energy efficiency has always been a driving force for making reforming technology more economical, the push today is toward reducing the carbon footprint of the plant. That means improvements in reformer design, heat integration and catalysts.

Also, "the shale gas boom in the United States was one of the biggest game changers in the past 10 years," says Christian Librera, head of Business Segment Syngas at Clariant Catalysts (Munich, Germany; www.clariant.com). Abundant and much cheaper resources have enabled the U.S. to significantly increase production of oil and natural gas. This has contributed to the fact that the U.S. will soon become a net exporter of methanol, and potentially ammonia, he says. "Further advantages to the U.S. are that methane-based syngas has a lower CO_2 footprint, and is more cost-competitive compared to China's coal-based syngas."

"In Europe, due to comparably high feedstock costs, the focus is on establishing more cost-efficient syngas production processes, and reducing related CO_2 emissions through different innovative technologies — energy efficiency is and will remain the prevailing theme," Librera continues. "In this context, renewables are also becoming more important, and are being explored to a larger extent than in other regions. Water electrolysis through renewable energy will play an increasingly important role in the future, as will syngas generated from biomass. All this will most likely happen gradually, rather than as a step change," says Librera.

In the meantime, traditional reforming will continue to play a leading role for the production of syngas. What follows is a small sample of some of the new process innovations for improving the efficiency of methane reforming, as well as some emerging technologies for the future.

Methane reforming

With the availability of abundant and inexpensive natural gas, the reforming of methane into syngas is of growing importance for the production ammonia, methanol, dimethyl ether (DME) and many other chemicals.

There are basically four main technologies used for reforming methane into syngas: steam-methane reforming (SMR), heat-exchange reforming (HExR), autothermal reforming (ATR) and partial oxidation (POX). Deciding which technology to use depends on a number of factors, including feedstock availability and desired product (For a good overview, see "A Guide to Methane Reforming," *Chem. Eng.* 2015, pp. 40–46). Today, SMR accounts for about 50% of the H_2 produced in the world. This highly endothermic reaction takes place in an array of catalyst-filled tubular reactors that are heated to high temperatures in a fuel-fired furnace.

Reducing steam export

One current trend in the industry is the requirement of minimum or zero co-produced steam from small to large steam-reforming units, says Alexander Rösch, director HYCO product line, Air Liquide Engineering & Construction (Frankfurt, Germany; www.engineering-airliquide.com). This results from efficiency programs in petroleum refineries and improvements of technologies, and is addressed by several technology bricks, like pre-reforming (single or multi-stage), heat integration, or new technologies. "As part of our portfolio of hydrogen technologies, we have recently developed SMR-X, a next-generation technology that produces H_2 without co-producing excess steam," says Rösch. Compared with conventional SMR, SMR-X features higher thermal efficiency at low steam co-production ratios and emits lower levels of CO_2, he says.

With SMR-X (Figure 1), the feed

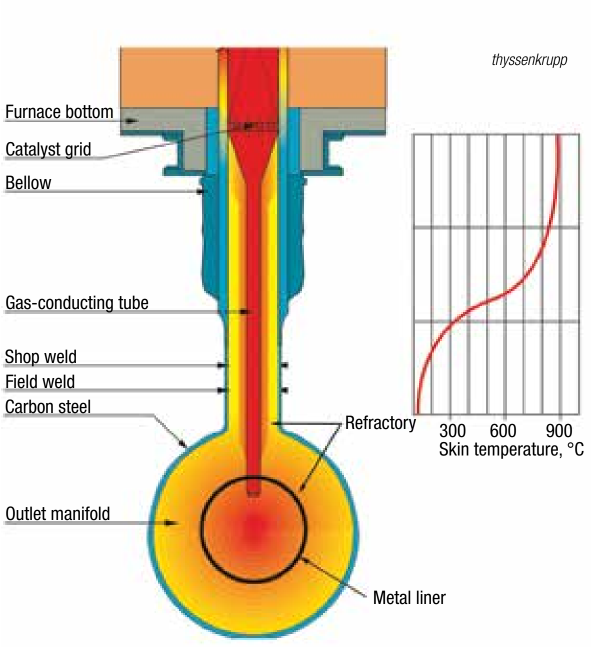

FIGURE 2. The proprietary Uhde cold-outlet manifold system uses standard carbon steel instead of expensive heat-resistant austenitic steels

gas is transformed into H_2 through a reforming process driven by heat (700–900°C). Instead of generating steam from excess heat, the reformer tubes have been optimized to re-use the energy in the reforming process, Rösch explains.

"SMR-X technology provides lower production cost through internal process-heat recovery. While the bulk of heat to SMR-X is provided via radiative heat transfer, around 20% of the process heat is supplied by internal heat exchange. This results in reduced furnace size and fewer reformer tubes compared to traditional steam reformers. Additionally, the internal steam system design is simplified, since no steam is exported," Rösch says.

With SMR-X, Rösch continues, the desulfurized feed gas is mixed with process steam, and passes through catalyst-filled reformer tubes and is then cooled by heat exchange with process gas inside the tubes. Overall feed and fuel consumption, as well as CO_2 emissions are reduced by 5% compared with a conventional SMR, he says.

Last year, Air Liquide and Covestro AG (Leverkusen, Germany; www.covestro.com) signed a long-term contract for the supply of hydrogen at Covestro's production site in the port area of Antwerp, Belgium. Air Liquide will invest €80 million in the construction of a "new generation" H_2-production unit. The plant will be fitted with SMR-X technology. The H_2 produced will also enable Air Liquide to supply customers in this industrial basin in Europe. In connection with this new long-term contract, the H_2 will be used in the production of aniline, which is one of the base chemicals for polyurethanes. This new SMR-X unit is expected to start operation in 2020.

Marco Scholz, head of Process Group Hydrogen and Syngas OU Refining & Petrochemicals, thyssenkrupp Industrial Solutions AG, Business Unit Chemical & Process Technologies, (Dortmund, Germany; www.

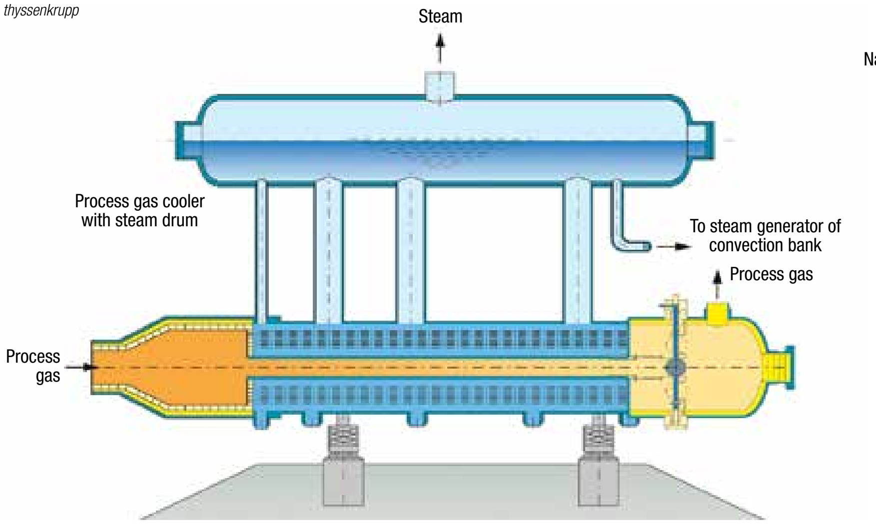

FIGURE 3. **The heart of heat integration is the process gas cooler/HP steam generator, in which clean, high-pressure (HP) steam is produced by cooling process gas from the reformer**

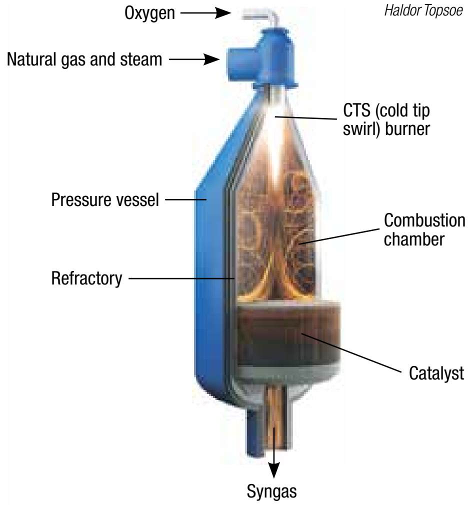

FIGURE 4. **The heart of the SynCOR process is the autothermal reformer, which uses pure oxygen to convert CH_4 into syngas operating at a low carbon-to-steam ratio of 0.6**

thyssenkrupp-industrial-solutions.com) agrees that a current trend in H_2 production by SMR is the design and building of low steam exporting plants with minimized feed and fuel consumption. "High-pressure (HP) steam is normally always produced as a byproduct in steam reformer plants. Reducing the feed and fuel consumption decreases the annual opex (operating expenditures) of the SMR plant. The overall efficiency of the plant is even higher when a certain amount of HP steam is exported. It can be used for driving large rotating equipment, as well as for heating or reaction purposes," says Scholz.

SMR plants from thyssenkrupp feature a dual steam system that allows steam production with guaranteed higher quality of export steam. Steam generated from process condensate is exclusively used within the steam-reforming process. This totally eliminates the need to return process condensate to a boiler feed-water-treatment unit (for example, a stripper) and reduces the amount of volatile organic components, explains Denis Krotov, senior process engineer and product manager at thyssenkrupp.

Thyssenkrupp Industrial Solutions invented the cold outlet manifold (Figure 2), which is applied in numerous NH_3, H_2 and methanol plants built by the company, says Krotov. To further improve the heat distribution within the concrete of the outlet manifold, thyssenkrupp currently applies an eccentric outlet manifold and a special design of transition piece from reacting tube to outlet manifold ("gas conducting tube"). Consequently, the surface temperature of the pressure shell is well balanced and thermal expansion is very even so that resulting thermal tensions are minimized and unwanted hot spots are excluded, explains Krotov.

The heart of the heat integration is the process gas cooler/HP steam generator (Figure 3). In this apparatus, clean HP steam is produced by cooling process gas from the reformer and functioning as a natural circulation boiler. The process gas cooler has an integrated bypass system and is maintenance-free. Its functionality has been proved in numerous projects, says Scholz. "Depending on the customer's request, the steam pressure and the degree of superheating can be selected as desired."

Autothermal reforming

"To meet the growing demand, future methanol plants will incorporate large capacities coupled with low production costs, high energy efficiency and the lowest possible environmental pollution," says Scholz. "Autothermal methane reforming (ATR) combined with energy-efficient methanol synthesis and distillation processes is the answer to these requirements," he says.

ATR uses pure O_2 to partially oxidize methane into syngas. This reaction is very exothermic, and takes place at very high temperatures (950–1,050°C, compared to 750–959°C for SMR), which requires robust catalysts. Haldor Topsoe A/S (Lyngby, Denmark; www.topsoe.com) pioneered advanced ATR in the 1990s, and commercialized its low steam-to-carbon (S/C) ATR for smaller-sized units in 2002. Recently, the company introduced its SynCOR technology. The core of the SynCOR process is the ATR (Figure 4) that reforms methane into a syngas with S/C ratio of only 0.6, which means the steam throughput is reduced by 80% compared to conventional SMR plants, says Svend-Erik Nielsen, a fellow at Topsoe. The SynCOR process is applicable for a number of downstream products, such as NH_3, methanol, H_2, gas-to-liquids (GTL), CO, formaldehyde, DME and other chemicals.

With the trend for building large, single-train plants, economy of scale is very important, and ATR offers unique scaleup advantages over SMR. Unlike SMR, which requires increasing the number of reformer tubes for scaleup, an ATR scales up on the diameter of the reactor, explains Nielsen. "This means the capital expenditures (capex) for a ATR plant are significantly lower than that of a SMR for large plants," he says.

The most recent addition to the SynCOR family is SynCOR Ammonia, which makes it possible to use ATR for single-train ammonia plants with a capacity of 6,000 metric tons per day (m.t./d). This has been made possible with the commercialization of Topsoe's latest high-temperature shift catalyst, SK-501 Flex, which uses a promoted zinc/aluminum spinel structure instead of the traditional iron/chromium structure. It removes the risk of forming Fischer-Tropsch

byproducts at low steam-to-carbon ratio, which is a limitation of the traditional high-temperature shift catalyst, and thereby enables NH_3 producers to save on feedstock and energy, or boost production by up to 5% in their existing set-up in a revamp situation. The new catalyst also eliminates the risks related to handling of Cr^{6+}, both to the environment and plant personnel, says Nielsen.

New catalysts

"Our latest innovations, the steam methane reforming catalysts, ReforMax 330 LDP Plus (standard) and ReforMax 210 LDP Plus (lightly alkalized), were developed to solve our customers' challenges of increasing feedstock prices and energy costs by enhancing the efficiency of plant operations," says Clariant's Librera.

Chemically based on the industry-proven ReforMax LDP series, the catalysts' new and unique eight-hole flower-like shape (Figure 5) is designed to optimize catalyst geometry and mechanical strength. This results in a drastically reduced pressure drop (of up to 20%) across the reactor tubes compared to the previous catalyst generation, without compromising activity or stability, explains Librera. The design allows increases in gas throughput (by up to 11%), lowers greenhouse-gas emissions and leads to significant energy savings, he says.

The new ReforMax LDP Plus catalyst series has already demonstrated its performance advantages in several commercial facilities, including H_2 units in the U.S. and two major NH_3 plants in Europe. The facilities are benefitting from the expected pressure drop reduction across the catalyst bed, leading to a significant increase in energy efficiency — contributing to minimizing CO_2 footprint while also improving the cost competiveness of the plant, says Librera.

Another way to reduce pressure drop in steam reformers is the Catacel SSR catalyst from Johnson Matthey plc (JM; London, U.K.; www.matthey.com). In the Catacel SSR system (*Chem. Eng.*, March 2010. p. 11), which JM acquired in 2014, alloy strip is formed into engineered supports called fans, which are coated with a nickel-based steam-reforming catalyst. The fans are stacked inside of the reformer tubes. This design offers many advantages over traditional ceramic pellets, and provides lower pressure drop, high heat transfer and high activity, says the company. Catacel SSR is said to represent the single biggest step forward when it comes to the development of catalyst shape. Compared to standard pellets, Catacel SSR leads to a 20% decrease in pressure drop. "The value of increased throughput when exchanging an old catalyst with a new optimized one can in some instances pay for the optimized catalyst charge in less than one year, says the company.

The last two years have seen a commercial breakthrough for the technology from the initial adopters in 2008, with smaller reformers (containing up to ten tubes), to conventional reformers, a market where

FIGURE 5. The eight-hole flower-like shape of the ReforMax LDP series catalyst is designed to optimize catalyst geometry and mechanical strength, and results in a reduced pressure drop across the reactor tubes

there are up to a thousand tubes in a single reformer, says Michael Hepworth, engineering technology manager at JM's Catacel Technology Center in Ravenna, Ohio. As of late 2018, Catacel SSR is operating in eight reformers globally, including an over 50-tube and an over 90-tube conventional, top-fired reformer. Product is being manufactured for two more conventional reformers with over 100 tubes, establishing SSR in the wider reforming market, says Hepworth. "This has resulted in continuous, two-shift operation at JM's Ravenna manufacturing facility," he says. (This technology is one of the six finalists vying for the 2019 Kirkpatrick Chemical Engineering Achievement Award.)

Dry reforming

Methane conversion with CO_2 instead of steam (dry reforming) is an alternative route from methane to syngas. With this technology, CO-rich syngas can be generated as an important feed to form many products or intermediates, such as organic acids, phosgene, polycarbonates and agricultural chemicals. On-site production of CO via CO_2-reforming of methane can be favorable due to economic and (transport) safety aspects, says Clariant's Librera. "Furthermore, the CO_2 footprint of the production site can be significantly reduced. Clariant provides a set of highly efficient catalysts for this application, and works in close cooperation with a reputable engineering partner for more than 20 years," he says.

Next year, BASF AG (Ludwigshafen, Germany; www.basf.com) and technology partner Linde AG (Munich, Germany; www.linde.com) plan to launch a new dry-methane-reforming catalyst (*Chem. Eng.*, February 2019, p. 9). To perform dry reforming, BASF developed two spinel-type catalysts based on nickel and cobalt. In addition to reducing the steam demand by up to 60%, dry reforming produces a CO-rich syngas ($CO:H_2$ = 1:1), which is optimal for directly making DME. A new catalyst system — a combination of two catalysts that perform bifunctional catalysis — is also being developed for the direct conversion of syngas to DME. The zeolite-based catalyst system also has a "self-cleaning" feature that prevents deactivation, says BASF. Commercial launch of the syngas-to-DME catalyst is planned for 2022.

Meanwhile, Japanese researchers are also working on new catalysts for performing dry methane reforming at low temperatures (*Chem. Eng.*, May 2019, p. 11). Although dry reforming has the potential to reduce CO_2 emissions, it is also prone to carbon deposition, especially at lower temperatures. The catalyst — a metal/oxide nanocomposite with tailored 3-D topology — is being developed at the National Institute for Materials Science (NIMS, Tsukuba City, www.nims.go.jp), in collaboration with scientists from the Kochi University of Technology and Tokyo Institute of Technology. In laboratory studies, the catalyst was shown to activate CO_2 and CH_4 at 623K, and promote low-temperature dry reforming at 723K for over 1,000 h — ten times longer than traditional supported catalysts.

Electrical heating

Another way to reduce CO_2 emissions from SMR is to use electrical heating instead of conventional fossil-fuel-fired furnaces. This is becoming more feasible as the cost and reliability of renewable electricity (wind or solar power) becomes available.

Last month, researchers from the Technical University of Denmark (Lyngby; www.dtu.dk) the Danish Technological Institute (Tåstrup; www.dti.dk) and Haldor Topsoe reported their studies on a compact, electrically heated reformer in the journal *Science*.

The laboratory reactor consists of a FeCrAl-alloy tube, which is coated on the inside by a 130-µm nickel-impregnated catalytic washcoat. The catalyst is directly heated by passing an alternating current across the two ends of the tube (resistive or Ohmic heating). Feed gas — a mixture of CH_4, H_2O and H_2 — passes through the reactor and is reformed into syngas at a temperature of up to 800°C. The electrical heating is reported to supply a nearly constant heat flux, which keeps the gas mixture near equilibrium and results in a better utilization of the reactor volume compared to conventional reformers. It also limits carbon formation.

The technology has the potential to reduce the size of SMRs by a factor of 100.

BASF, together with Linde and academic partners, is also developing an electrically heated furnace ("E-Furnace") for high-temperature catalytic reactions. Although the main target for this low-voltage, high-current furnace is for reducing the CO_2 footprint of catalytic crackers, the technology is also suitable for SMR. When combining the E-Furnace with dry methane reforming, syngas production could actually become a net CO_2 *consumer* of up to 490 kg CO_2/TNm^3 of syngas, compared to 350 kg CO_2/TNm^3 *emitted* by conventional reforming, says the company.

In another long-term research project, BASF, together with Linde, thyssenkrupp and academic partners, is developing furnace technology for pyrolyzing methane into H_2 and carbon. The process is said to require significantly less energy than the water electrolysis, and the solid carbon product can be used in the aluminum, steel and other industries. Laboratory studies have already been conducted using a moving-bed reactor that is heated by electrical induction. The second three-year phase of this project is now underway to further develop the proof-of concept for the reactor design and the carbon outlet. ■

Gerald Ondrey

New Instruments Designed to Take the Heat

Temperature measurement and control equipment is being re-vamped to stand up to challenges of the chemical process industries (CPI)

IN BRIEF

TEMPERATURE MEASUREMENT & CONTROL

ACCURACY, RELIABILITY AND REPEATABILITY

INSTRUMENTATION ADVANCEMENTS

NON-INTRUSIVE MEASUREMENTS

While the basic premise of temperature measurement instruments hasn't seen drastic changes in recent years, equipment is receiving updates that make it more user friendly and robust in an effort to increase accuracy, reliability and repeatability, which are essential for chemical processors who rely on temperature measurements for product quality and safety.

Temperature measurement & control

Why are temperature measurement and control so important for chemical processors? Jan-Marc Featherston, sales manager with INOR Process AB (Beverly, Mass.; www.inor.com) explains it simply: "Processors need to know and control the temperature, as well as other parameters, of the process in order to make their product precisely and of the same quality every time," he says. "Think of it like making chocolate chip cookies. You don't need to know the exact temperature to make them, but you won't be able to make them consistently, with the same quality or as quickly as you like without knowing the precise temperature at which you're baking them."

More precisely, because temperature plays a critical role in most chemical processes, it can affect everything from product quality to process efficiency to energy usage to safety. When it comes to process efficiency, for example, if the temperature is too low, it may take longer for the reaction to complete, explains Nicholas Meyer, product marketing manager for Yokogawa Corp. of America (Sugar Land, Texas; www.yokogawa.com). "It can also affect product quality," he says. "There may be side reactions and a particular temperature range could favor one of the products over the other, so if you're trying to eliminate byproducts or achieve a particular ratio of product, the temperature would be very important there. Likewise, if you get something too

INOR

FIGURE 1. The INOR Connect application allows operators to connect to the transmitter with a smartphone or tablet using Bluetooth or near-field communication so they can configure and monitor temperature transmitters without supply voltage and cables

hot, it could burn or degrade the product."

Meyer continues: "Temperature also impacts energy usage. You likely want the process to go as fast as possible, so the initial thought may be to put a lot of energy into it, but eventually you get to a point where that diminishes your returns because the amount of energy you're putting in is costing more than the worth of the quality of product you are getting out."

And, regarding safety, chemical processes may involve volatile reactions or potential runaway reactions so the temperature needs to be monitored closely to ensure that it doesn't get to that point, says Meyer.

In addition, chemical plants and petroleum refineries rely on safety instrumented systems (SIS), which use instruments and controls to keep the process running in a safe manner. "If you're going to rely on instruments to provide that safe mechanism, it's now not just a nice measurement to have, temperature measurement becomes part of an essential system that keeps the

process operating safely," explains Tony Maupin, market segment manager with WIKA USA (Lawrenceville, Ga.; www.wika.com).

Accuracy, reliability, repeatability

When seeking temperature measurement instrumentation, processors usually demand accuracy, reliability and repeatability in order to achieve efficient processes that produce high-quality product in a safe and energy-efficient manner.

Accuracy is important when the processor is looking at very critical measurements that affect product quality. "The margin could be very slim between having a successful reaction and burning or degrading a product," says Meyer. "In those cases, accuracy is a very important feature."

Repeatability, or stability, of instrumentation allows processors to know that the same process conditions are being repeated. "Many customers will say accuracy is most important, but that's not always true," says Ehren Kiker, product marketing manager with Endress+Hauser (Greenwood, Ind.; www.us.endress.com). "Accuracy implies that the instrument measures with plus or minus a certain percentage of accuracy, but that means today the measurement could be plus 1% and then tomorrow it could be minus 1%. But, with a repeatable or stable measurement, I know it will always be off by plus 1% and can correct for that. When it's all over the map, even if only by plus or minus 1%, it's not as easy to account for."

And, reliability is also important. "If you have a failed measurement in a batch process, you could waste the batch, cause rework and negatively impact profits," says Yokogawa's Meyer. "Likewise, if the measurement points go out during a continuous process, you could end up with unplanned downtime, which also equals lost profit."

Instrumentation advancements

Often, the user friendliness of not just instrumentation, but of programming techniques and calibration, can impact accuracy, repeatability and reliability of the measurement. For this reason, equipment providers are making it easier to use. To simplify programming and monitoring of temperature transmitters, some manufacturers are adding Bluetooth capability to their instruments.

INOR, for instance, has the INOR Connect application (Figure 1), which allows operators to connect to the transmitter with a smartphone or tablet using Bluetooth or near-field communication so they can configure and monitor temperature transmitters without supply voltage and cables. The application offers the same configuration options as INOR's existing ConSoft transmitter software, but with a more user-friendly interface. "The app gives users the ability to communicate and configure transmitters with their phones, which makes it easier to get the product installed in their process because they can now program the transmitter right in the field. This is a huge help when something goes down at an inopportune time and needs to be replaced and programmed as quickly and easily as

possible," says Featherston.

Likewise, Endress+Hauser is releasing transmitters with Bluetooth capability. "The idea is that we wanted to make it easier for users to access the transmitter that's connected to a sensor — whether it's to configure it, get diagnostic information or just see the current measurement value — without having to climb into a unit," says Kiker. The company's SmartBlue App allows users within a radius of up to 20 meters of the device to commission and operate it. For maintenance purposes, all data are at hand in real time and are encoded for secure data transformation. The application helps increase safety because employees no longer have to access hazardous areas, saves time via mobile access to the devices and increases reliability because there is no data loss during commissioning and maintenance.

Endress+Hauser

FIGURE 2. StrongSens can be supplied in temperature assemblies suitable for chemical processes where excessive vibration can lead to sensor failure

There are also advances in calibration equipment, which is essential because drifting impacts accuracy and repeatability. "If they aren't getting a reliable measurement all the time, due to degradation of their instruments, that can cause a process shift they aren't aware of," says Scott Crone, North American sales manager with Ametek Sensors, Test & Calibration (San Luis Obispo, Calif.; www.ametekstc.com). "However, a lot of companies rely on just a signal measurement rather than taking the sensor out of the process to save time. But if you're not checking the instrument with an actual temperature source, you won't really know if it's subject to degradation, which can impact quality and efficiency."

Processors often cite efficiency as one of the reasons they don't make proper calibration a priority, says Crone. One way to make it more efficient is to switch from liquid baths to dry block calibration when possible. "There have been a lot of advances in dry block technology and they are available now for a wider range of applications," says Crone. In addition, there are models that approach the homogeneity, accuracy and performance of a wet bath. Also, dry blocks are much faster. "It used to be that the [technicians] had to sit there and watch the calibration during a switch test, but we have automated switch tests incorporated into the dry block. They simply put the sensor in the dry block, put the leads onto the switch and run the test. The operator doesn't need to be there when the test is running," he says. "This means they can be deployed to do other things, which greatly raises efficiency in the plant because some switch tests, when getting to higher temperatures, can take hours to complete."

He adds that many dry blocks now also offer multi-zone control and dynamic load compensation (DLC) technology, which ensures that the well stays stable and the homogeneity is very good.

Ametek STC's RTC Reference Temperature Calibrators, for example, feature wide temperature ranges, DLC technology, which assists with temperature uniformity in the insert, even when calibrating large sensors or many sensors at a time, as well as dual- and triple-zone temperature control, which provide temperature homogeneity in the well.

In the chemical process industries (CPI), the difficult environment can often disrupt sensitive instrumentation, impacting accuracy, repeatability and, especially, reliability, so equipment providers are working on technologies that are more robust in order to function in harsh chemical processes.

"The chemical industry is fraught with environmental challenges and, at the same time, safety and operations excellence are big concerns," says WIKA's Maupin. "So [chemical processors] want reliable products and they don't want to lose the sensor in the process."

For this reason, equipment providers are designing products to be longer lasting, even in harsh environments. For example, notes Maupin, WIKA makes a thermocouple that is finding use in the production of low-density polyethylene (LDPE), which is an extremely high-pressure process. "Thermocouples have to withstand those pressures and still be reliable indicators, because processors use them to control the process and detect whether or not the reactor is in danger of decomposition, which can destroy the reactor and must be detected early," he says. "Any thermocouples in these processes have to respond very quickly to changes in temperature and have to withstand very high pressures."

The answer is WIKA's TC90, which is a high-pressure thermocouple made using special manufacturing processes. The measuring assembly is sealed by means of metal-to-metal sealing, high-pressure threaded connectors or sealing lenses. And, to ensure sufficient joint integrity between the mineral-insulated (MI) cable and fitting, vacuum brazing is used to minimize void spaces and create high-strength joints.

And, for chemical and refining processes faced with high vibration, Endress+Hauser developed the iTHERM StrongSens line of sensors (Figure 2). "Pipe vibrations are not good

FIGURE 3. Ametherm's line of ACC NTC thermistors is made using nanopowders to make them more robust in difficult environments

Ametherm

Emerson

FIGURE 4. Emerson's Rosemount X-well uses a thermal conductivity algorithm and an understanding of the conductive properties of the temperature measurement assembly and piping to accurately measure internal process temperature

Yokogawa

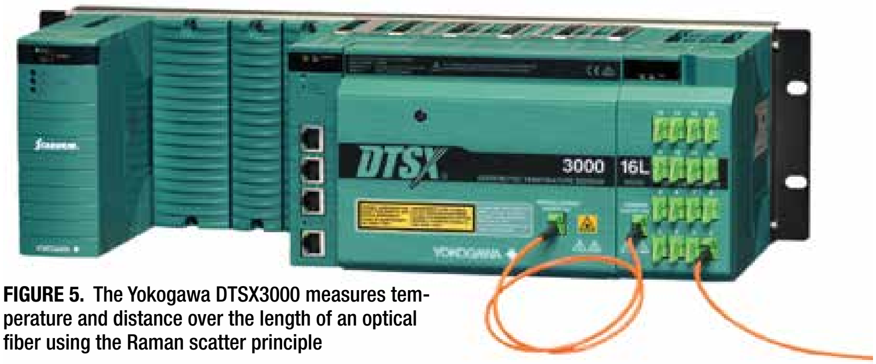

FIGURE 5. The Yokogawa DTSX3000 measures temperature and distance over the length of an optical fiber using the Raman scatter principle

for temperature sensors because the wires inside the sensors are thin, delicate wires, which tend to break when you start shaking them too much," he says. To combat the problem, the company developed an RTD sensor featuring StrongSens technology designed for high-vibration applications. "Typical thermocouples can handle 3G of vibration before wires break. But we've done things with the bonding method used in the sensor tip and supported it with wiring so that it can handle vibration up to 60G," says Kiker. "So, if they do have temperature measurements in an area where they can't get away from pipe vibration, StrongSens gives them something they can use that will be much more robust, resulting in longer product life and less downtime."

And for thermistors used in lower operating ranges (–40 to 250°C), there have been advances made in the oxide powders used to make the sensors. "Oxides powders were previously only available in micron sizes, but now we are able to get them in nanometers," says Mehdi Samii, vice president of engineering with Ametherm (Carson City, Nev.; www.ametherm.com). "Why is this important? The smaller particle size of the oxide powder makes it easier to produce a chip or disk that almost reaches theoretical density. This results in thermistors that are more rugged, repeatable and extremely durable. They can now withstand very drastic thermal shocks and vibrations without affecting repeatability, accuracy and thermal response. This enhances the product very much." The company's line of ACC NTC thermistors is made with the nanopowders (Figure 3).

Non-intrusive measurements

There are also some applications in which the material is either too corrosive, the environment too harsh or the application too tricky to use traditional measurement techniques effectively or efficiently. For these applications, there are non-intrusive technologies.

"There are times when the process itself is difficult to measure due to caustic or abrasive materials or you may not want to drill into a pipe and create a potential leak point, but traditional surface temperature measurement does not provide an accurate or repeatable representation of the internal process temperature, so we're developing technologies that don't require penetration, but still provide accurate measurement of internal process temperature," says Kevin Stultz, global product manager with Emerson Automation Solutions (Shakopee, Minn.; www.emerson.com).

Emerson's Rosemount X-well technology delivers accurate process temperature without thermowells or process penetrations (Figure 4). Using a thermal conductivity algorithm and with an understanding of the conductive properties of the temperature measurement assembly and piping, this non-instrusive temperature sensor solution is able to accurately measure internal process temperature.

For other applications, such as those involving reactors or vessels where hot spots or temperature differentials can indicate that the product is not being mixed well or other issues, it can become cost prohibitive to employ traditional single insertion probes, says Yokogawa's Meyer. "We offer the DTSX series of fiber optic sensing cables to provide continuous temperature sensing for long distances," he says. "The solution provides enhanced visibility into the process because you can completely wrap a reactor or a vessel and program in temperature zones, which allows users to measure temperature all along the string."

The Yokogawa DTSX3000, for example, measures temperature and distance over the length of an optical fiber using the Raman scatter principle (Figure 5). A pulse of light launched into an optical fiber is scattered by fiberglass molecules as it propagates down the fiber and exchanges energy with lattice vibrations. As the light pulse scatters down the fiber optic cable, it produces longer wavelength and shorter wavelength signals, of which both signals shifted from the launch of the light source. The intensity ratio of the two signals components depends on the temperature at the position where the Raman scatter is produced.

Temperature is determined by measuring the respective intensities of the longer and shorter wavelength signals. Furthermore, part of the scattered light, known as the backscatter, is guided back towards the light source. The position of the temperature reading can thus be determined by measuring the time taken for the backscatter to return to the source.

No matter what your process, its environment or your temperature measurement needs, there is likely an instrument that can stand up to the challenges to help bring efficiency, quality and repeatability to your process. ■

Joy LePree

Focus on Pumps

Pump Engineering

Wanner Engineering

Force Control Industries

Finder Pompe

Self-priming, liquid-ring pumps enable hygienic operation

The CFS AS/ASH Series of pumps (photo) use a self-priming, liquid-ring hygienic design. They are manufactured in cast 316L stainless steel and are electropolished as standard, so they have no "dead spots" that could result in product contamination. This makes them ideal for clean-in-place applications in pharmaceutical, food, dairy and brewery applications, says the manufacturer. They are available in single- and two-stage options with IEC motors fitted as standard. The range includes seven models, which are capable of handling flowrates ranging from 2 to 55 m^3/h (2,000–55,000 L/h), at heads to 60 m (6 bars). They can also be used in applications where liquids have entrained air or gas. A range of end connections, and ATEX-approved versions are available for enhanced safety. — *Pump Engineering Ltd., West Sussex, U.K.*
www.pumpeng.co.uk

Sealless pumps eliminate emissions, trim maintenance

The Hydra-Cell T200 Series medium-pressure pumps (photo) feature a sealless design that avoids the maintenance problems of mechanical or dynamic seals and packing that can wear and leak. With flowrates of up to 95 gal/min and a maximum pressure rating to 3,500 psi, the Hydra-Cell T200 models are ideal for high-capacity applications including saltwater injection, bulk transfer and hydraulic lift in oilfields and steam generation, reverse osmosis, boiler feed and high-pressure feed. The patented design employs hydraulically balanced, multiple diaphragms that enable the pump to handle high pressures with low stress, and abrasive particulate matter up to 800 microns in size. The sealless design eliminates the potential leak path, thereby eliminating the chance of hazardous emissions, and helping to reduce maintenance and cleanup costs associated with packed-pump leakage. This also eliminates the need for external lubrication and maintenance, as well as plunger wear problems. — *Wanner Engineering, Minneapolis, Minn.*
www.wannereng.com

This compact clutch allows for remote pump actuation

The PosiClutch 200 Series PTO clutch (photo) is a hydraulically actuated, microprocessor-controlled Oil Shear PTO clutch, which is designed for high-volume pump applications. The clutch mounts on a diesel engine with an SAE 00 flywheel housing, and can include up to four pump pads to drive additional hydraulic pumps, to 400 hp. This enables remote engagement of pumps, which makes them applicable in wastewater-treatment, flood-control and other high-volume applications. Advanced engineering-design elements eliminate the need for separate transmission-fluid cooling equipment, thereby eliminating components, hoses and fittings that are prone to leakage and failure, says the company. The clutch has a length of just 33.25 in., including sheave support bracket. It features an enclosed, heavy-duty, foot-mounted, cast-iron sealed housing that enables operation in dirty, dusty and wet environments, indoors or outside. — *Force Control Industries, Fairfield, Ohio*
www.forcecontrol.com

This pump is designed for low-capacity, high-head situations

The patented DualPEP (photo) is a two-stage, overhung pump that uses two low-flow-design impellers in a back-to-back configuration, inside a radially split, barrel-shaped, centerline-suported integral casing to maintain an end-top nozzle configuration. It meets API 610 11th Ed. design requirements, and is designed for applications that have relatively low-flow, high-head requirements, and are handling hot, corrosive or viscous fluids, says the company. The pump is said to have no backflow and high stability at low-flow conditions, has relatively low NPSHr without the use of inducers, and is designed for

Note: For more information, circle the 3-digit number on p. 62, or use the website designation.

high reliability and low maintenance, even in heavy-duty applications. Two configurations are available (one for space-constrained settings). — *Finder Pompe S.r.l., Merate, Italy*
www.finderpumps.com

This lightweight pump is ideal for environmental applications

The SlimJim Electric Pump System (photo) is particularly well-suited for environmental-remediation sites and landfills. It requires no separate control panel and features built-in automatic on/off start and run-dry protection. It offers plug-in operation at 115- or 230-V single-phase power. With a 4.5-in. outer dia., the pump is compact and easy to handle and weighs only 22 lb. It is ideal for smaller-diameter risers, such as cleanouts, collapsed pipes or bent risers, says the manufacturer. The pump's optional three-phase operation with control panels adds several benefits, including variable speed, programmable from a smart phone, and the ability to view and change pump data and parameters. With available flowrates of up to 30 gal/min, the SlimJim can be used in vertical or horizontal applications, and is suitable for the same applications as air-powered pumps, but operates at higher flowrates. The stainless-steel motor and pump casing and high-density polyethylene protective shroud resist corrosion. A chemical-resistant Teflon version is also available. — *Q.E.D. Environmental Systems, a subsidiary of Graco, Dexter, Mich.*
www.qedenv.com

Q.E.D. Environmental Systems

This intrinsically safe pump prevents fluids at the shaft seal

The intrinsically safe MPCVAN pump (photo) is a dry-running magnetic-drive centrifugal pump that is suitable for fluids that are hot, abrasive and corrosive. The vertical pump is hermetically sealed, with a shaft seal concept based on the complete hydrodynamic relief of the shaft seal and bearing unit, says the manufacturer. The penetration of product fluid or vapors into the shaft seal area is prevented by impeller back vanes during operation, and a gas barrier during stand-still operation. — *Paul Bungartz GmbH & Co. KG, Düsseldorf, Germany*
www.bungartz.de

Paul Bungartz

Large-hp, single-phase motor is ideal for industrial use

The Belle Single-Phase Motor (photo) is said to be the world's first 100-hp single-phase electric motor. It uses patented Written-Pole technology to deliver a 100-hp single-phase motor that is compatible with readily available single-phase utility services. This eliminates the need for phase converters or complex variable-frequency drive installa-

Single Phase Power Solutions

Atlas Copco

Cole-Parmer

Watson-Marlow Fluid Technology Group

Leybold

tions, and minimizes voltage sags and flicker on long, single-phase distribution lines. It is ideal for industrial applications where three-phase power is not readily available or cost-effective, to power equipment such as pumps, compressors, injection wells, blowers, fans, dryers water- and wastewater-processing equipment and more. Rated as a 100-hp, 460-V, 1,800-rpm electric motor, it is suitable for indoor or outdoor installation. The NEMA 449T frame motor weighs about 2,700 lb and draws just 170 A at full load, says the company. In addition to a full range of Belle Motors from 30 to 100 hp, the company also offers a 1–to–3 MicroGrid solution that generates clean, high-quality, three-phase power from a single-phase line for packaged equipment requiring a three-phase power source. — *Single Phase Power Solutions, Cincinnati, Ohio*

www.sppowersolutions.com

This compact, dry vacuum pump eliminates contamination

The DHS 065-200 VSD+ dry screw vacuum pump (photo) is built for rapid cycling and continuous operation. It requires no water or oil cooling, eliminating a source of contamination. Certified as oil-free in the Class Zero category of ISO Standard 8573-1, the pump is free of oil emissions, including aerosol oil content in its outlet air stream. Its reduced number of parts within the pump, combined with the variable-pitch screw design, help increase efficiency and reduce maintenance, according to the manufacturer. The vibration-free pump is housed in a noise-reducing canopy, and is equipped and controlled with the MK5 Elektonikon and the company's Smartlink system, which integrates the pump to plant-management systems to provide status updates on running and stopped hours, warnings, faults and shutdown indications. — *Atlas Copco, Industrial Vacuum Div., Cologne, Germany*

www.atlascopco.com/vacuum

These pumps can be controlled remotely, via the Internet

Masterflex cloud-enabled pumps (photo) featuring MasterflexLive now meet 21CFR Part11 and EU Annex 11, according to the manufacturer. This new technology brings the internet of things (IoT) to pump applications, providing pump operators with the ability to remotely control and monitor pumps via the Internet, without the need to be onsite. When enhanced security, data control and electronic records are critical to the operation, companies can meet 21CFR Part 11 compliance with a low-cost subscription service. MasterflexLive is a secure, cloud-based platform for controlling and monitoring select Masterflex L/S and I/P pumps. Pump operators can monitor and adjust critical processes running 24/7 from anywhere with a data connection. This new smart technology, a first-of-its kind for peristaltic pumps, provides real-time control of all pump parameters, including speed, flowrate, dispense volume and more. Push notifications provide alerts for operating conditions and error messages. Hands-free operation allows control of pumps operating inside cleanrooms, glove boxes or isolation chambers. Access is easy from a computer, tablet or smartphone. — *Cole-Parmer, Vernon Hills, Ill.*

www.coleparmer.com

This dry pump is for electronics and semiconductor uses

The high-efficiency, low-power iXH Mk2 Series dry pump is designed for ultra-harsh process operations in the semiconductor, display, LED and solar photovoltaic manufacturing processes. This pump provides longer service life than its competitors, thanks in part to improved gas-barrier technology and thermal design improvements that help to reduce corrosion. Similarly, its energy-efficient roots mechanism can reduce input power by up to 60%, reducing both environmental impact and the cost of ownership, says the manufacturer. — *Edwards Vacuum, Burgess Hill, U.K.*

www.edwardsvacuum.com

These pumps optimize waterjet cutting systems

This manufacturer of ultra-high-pressure pumps and components for waterjet systems offers a variety of waterjet cutting products. The company offers the KMT Water-

jet Streamline PRO-III pump (with increased pressure to 90,00 psi), which joins the company's other product — the SL-VI pump (60,000 psi) and the TRILine pump (55,000 psi) — to meet the needs of any waterjet cutting machines. Thanks to the pump's increased water pressure and accelerated-velocity cutting stream, the use of abrasive additives can be reduced by as much as 50%, significantly reducing manufacturing costs while increasing throughput capacity of the waterjet cutting table, says the company. — *KMT Waterjet Systems, Baxter Springs, Kan.*
www.waterjet.com

Mobile metering is easy with this battery-operated pump

The latest member of the Qdos Series of chemical metering pumps are designed to provide accurate, linear and repeatable metering of fluids, even when pressure, viscosity and solids content vary. The latest addition to the Qdos family (photo) is designed for mobile and remote applications that can be powered by a 12–23-V d.c. power supply. The latest Qdos pump is designed for applications where a precise, closely controlled metering pump is required, but access to a grid power supply is not readily available or practical. Suitable for both remote static and mobile battery-powered applications, typical uses of the new 12–24-V d.c. version include remote water treatment and sampling, on-truck pumping operations, and more. For very remote applications, the self-contained pump is able to run from batteries that can be recharged via solar cells, other renewable energy sources or split charge relays. — *Watson-Marlow Fluid Technology Group, Wilmington, Mass.*
www.watson-marlow.com

Low-energy models join this family of vacuum screw pumps

This company has recently added several new products to its dry, compressing Dryvac Series of vacuum screw pumps (photo). The new Dryvac DV 200 and DV 300 pump sizes complement the existing product range of Dryvac 450, 650 and 1200, and offer the same benefits for applications that require a smaller pump size. These pumps feature low constant power consumption, and due to an optimized screw rotor design, the DV 200 and DV 300 minimizes power consumption, reducing both costs and carbon footprint for the operator. Able to operate reliably under harsh conditions and handle vapors, dusts and particles, these pumps are equipped with an automatic shaft-seal-purge control for optimal protection of shaft seals and bearings. Fieldbus and programmable logic controller (PLC) compatibility allow for connectivity to other devices, enabling realtime communications and control. — *Leybold GmbH, Cologne, Germany*
www.leybold.com ■

Suzanne Shelley

Endress+Hauser

Thermo Fisher Scientific

Andritz

R. Stahl

An IIoT platform for increased system availability

Netilion is an industrial internet of things (IIoT) ecosystem that combines applications and system components that significantly simplify system management and maintenance (photo). The Netilion Scanner application (app), as well as Netilion System Components, make it easy to monitor the installed base, while Netilion Analytics provides an overview of the installed instruments. Netilion Health visualizes and interprets the status of the installed base, thus enabling operators to quickly initiate maintenance measures when irregularities occur. And with Netilion Library, this company is offering an online data-management service for the entire lifecycle of the measurement point. — *Endress+Hauser AG, Reinach, Switzerland*
www.endress.com

Analyze low chlorine concentrations in wastewater

This company has developed a new total residual oxidant (TRO) analyzer to address the needs of the wastewater industry, which calls for a robust, dependable instrument capable of reliably measuring low parts per billion (ppb) chlorine concentrations in effluent and treated wastewater in line with stringent regulatory requirements. Operating on the U.S. Environmental Protection Agency (EPA)-approved iodometric electrode technology, the Orion 7070iX TRO Analyzer (photo) has a high sensitivity for low-level chlorine measurements down to 1 ppb, with 1 ppb resolution. For optimal application flexibility, the new analyzer also enables full range measurements up to 15 ppm. — *Thermo Fisher Scientific Inc., Waltham, Mass.*
www.thermofisher.com

A new range of fine screens for efficient wastewater screening

The new range of Aqua-Screen fine screens ensure optimum separation of suspended solids from water influent, thus supporting enhanced performance by the downstream wastewater-treatment process. The Aqua-Screen fine screen uses standardized and common frame parts, which reduces maintenance time and the number of spare parts required. Less than 30 min. are needed for replacement of complete filter elements. With this modular concept, the fine screen integrates all existing screening categories: Aqua-Screen T (photo) is a toothing system that allows effective, two-dimensional fine screening and a lifting capacity; Aqua-Screen P is a perforated plate system that allows circular, two-dimensional fine screening. Depending on the screening system selected, the Aqua-Screen can achieve a capture rate of up to 85%, says the company. The range also includes a complementary device for membrane bioreactor (MBR) protection, the Aqua-Screen MBR fine screen, which has a capture rate of up to 99%, the company says. — *Andritz, Graz, Austria*
www.andritz.com

Online learning modules on explosion-protection principles

This company is now offering four new online courses on the basic principles of explosion protection, appliances for use in hazardous areas (photo), maintenance and inspection, and preventive explosion protection as part of its diverse range of professional development and training courses. These interactive e-learning modules can provide a valuable addition to attending classroom-style seminars or educational conferences at your own pace. The courses are designed to provide preparatory material presentations or seminars, and updates of the latest trends, technology and scientific developments in the industry. They are also highly recommended for those looking to refresh their knowledge after a long period of time. — *R. Stahl, Waldenburg, Germany*
www.stahl.de

Conduct hydrostatic-pressure tests with this pressure gage

The Crystal XP2i Digital Pressure Gage (photo, p. 31) is an easy-to-use, rugged, digital gage that is used to both read and document hydrostatic pressure tests, offering precise, reliable information to ensure safety. The standard XP2i is designed for the rough, in-the-field environments in which many pipelines are located.

They are temperature compensated, so the accuracy of the gages will not be degraded if it's used between –10 to 50°C (14 to 122°F). For users looking to record the data collected from their testing, the XP2i with optional DataLoggerXP upgrade records up to 32,000 data points (as fast as one reading per second). Free software downloads the information to a spreadsheet for easy storage and accessibility. — *Ametek Sensors, Test, & Calibration, San Luis Obispo, Calif.*
www.ametekstc.com

Interface device family expanded for non-intrinsically safe signals

The IM12 interface devices now allow for the first time the benefits of this company's IMX12 series to also be available for non-intrinsically safe signals (photo). The IM12 devices are some of the slimmest on the market, and with a width of only 6 mm per channel, save space in the control cabinet. Their modern electronic design provides a high degree of investment security. The entire device series is certified for use in functional safety circuits up to SIL2. The IM12 devices process digital and analog signals from field devices, such as in the pharmaceutical industry or chemical industry. However, the IM12 devices also find suitable uses in factory automation, such as for temperature and speed measuring. Parameterizable variables can be accessed via IO-Link and Pactware or other FDT frameworks. — *Hans Turck GmbH & Co. KG, Mülheim an der Ruhr, Germany*
www.turck.com

Balance enclosure for critical laboratory procedures

The VSE enclosure (photo) is offered in 24-, 36- and 48-in. widths to accommodate an analytical balance and other small-scale laboratory processes. The enclosures are constructed of chemical-resistant metal framing and 1/4-in. thick clear acrylic side panels and viewing sash. Efficient air-flow design with airfoil and bypass, directs contaminates to baffled exhaust, thereby providing superior airflow and containment performance for user protection. The viewing sash is angled 15 deg. for ease of viewing comfort with 8-in. reach in opening height. — *Hemco Corp., Independence, Mo.*
www.hemcocorp.com

Standard compliant 'ready for use' burner safety

The HIMatrix Combustion SafeGuard (CSG; photo) is a range of preconfigured, cost-effective and future-proof SIL3 safety systems designed for direct use as burner firing systems and part of the company's Smart Safety Platform. HIMatrix CSG is designed as a "ready for use" solution: ready for use and flexibly parameterizable to almost every common type of gas burner. It allows combinations of different manufacturers on both the sensor and the actuator side. "Ready for use" also stands for a standardized solution that is completely pre-programmed. In addition to SIL3, the HIMatrix CSG family is certified according to the standards EN 298, EN 12067-2 and EN 1643 and EC-type tested according to the current Gas Appliances Regulation 2016/426 / EU (DVGW). With HIMatrix CSG, burners can be put back into operation faster. A complete fault diagnosis makes it possible to significantly reduce the downtime after a shutdown. — *HIMA Paul Hildebrandt GmbH, Brühl, Germany*
www.hima.com

Customized solutions for drying and storage of compressed air

This company offers solutions for drying and storage that are individually tailored to the requirements of the individual application. There are two dryer series specially designed for high-pressure applications. The high-pressure refrigerant dryers of the SRD series are suitable for drying air and gases with final pressures of up to 420 barg and achieve a pressure dew point of 3–5°C. They can also be used as gas coolers. The high-pressure adsorption dryers of the SDD series (photo), on the other hand, achieve reliable dew points of up to –40°C at final pressures of up to 350 barg. They are specifically designed and optimized for use with this manufacturer's high-pressure compressors. — *J. P. Sauer & Sohn Maschinenbau GmbH, Kiel, Germany*
www.sauercompressors.de ■

Gerald Ondrey

Ametek Sensors

Hans Turck

Hemco

HIMA Paul Hildebrandt

J. P. Sauer & Sohn Maschinenbau

Surface-Mediated Heterogeneous Catalysis

Department Editor: Scott Jenkins

Heterogeneous catalysis in industrial processes involves a complicated set of physical and chemical phenomena that help lead to products. This one-page reference provides information about the formation of products in an industrial process using solid catalyst materials.

Catalyst materials

Industrially, there are several important classes of heterogeneous catalysts, including metals, aluminosilicates and organometallic materials. Industrial catalysts are typically porous solid materials, or are chemicals containing such materials. Solid catalysts exhibit specificity for particular reactions and selectivity for certain desired products, that in most cases, cannot practically be achieved without catalysts. And because they are present in a different phase than the reactants (solid versus fluid), heterogeneous catalysts are easily separated from the reaction mixture. Ideal catalysts allow reactions to proceed at suitable rates under conditions that are economically profitable, and at as low a temperature and pressure as possible.

Surface-mediated reactions

Because of the presence of different phases, heterogeneous-catalyzed reactions involve transport of reactants to the catalyst surface, as well as adsorption onto, and desorption from, the catalyst surface. All reactants and products must make their way to and from the catalytically active surface, and this mass transport can strongly affect apparent reaction rates and selectivity. Several general mechanisms for heterogeneously catalyzed reactions are shown in the box. Individual steps for adsorption to the catalyst surface, reaction and desorption, are shown for a monomolecular reaction and two types of bimolecular reactions. The terms k_a, k_r and k_d refer to the rate constants for each process.

Surface area

To increase the chances of reactants encountering a catalyst active site, catalysts are highly porous and are designed with large internal surface areas. For example, zeolites are a particular class of aluminosilicates with well-defined microporous crystalline structures. Many different zeolites have been developed because of the different ways in which the atoms can be arranged. Zeolite materials can allow large vacant spaces in the three-dimensional structure that leaves room for cations, such as Na^+ and Ca^{2+}, and molecules such as water. The void spaces in zeolites are interconnected and form long channels and pores which vary in size among different types of zeolites.

These materials are widely used to catalyze a range of important reactions, such as fluid catalytic cracking (FCC), toluene disproportionation, aromatic alkylation, methanol-to-hydrocarbon (MTH) conversions and more.

Catalyst action

Catalysts increase reaction rates by providing a pathway, at the molecular level, for the reaction to proceed at a lower activation energy than the uncatalyzed reaction. A transition state is a conceptual construct that can be thought of as a transient, activated complex through which reactant molecules are transformed into products. The catalyst stabilizes the transition state in some way, lowering the energy required to transform reactants to products, without itself being chemically changed by the reaction.

Catalyst deactivation

Two primary mechanisms contribute to catalyst deactivation. Solid catalysts can be deactivated by fouling, which involves the formation of carbonaceous deposits on the catalyst surface (coking). These deposits, formed by undesirable decomposition of organic compounds, can block the pores of a catalyst, and prevent access to active sites. Catalysts can also be deactivated by poisoning, which occurs when impurities, such as sulfur, trace metals and others contained in the feed material, attach to the surface of the catalyst and prevent adsorption of the reactants.

Heterogeneous catalyst reaction mechanisms

Monomolecular

$$A_{gas} \underset{k_{-a}}{\overset{k_{+a}}{\rightleftharpoons}} A_{ads} \quad \text{Adsorption}$$

$$A_{ads} \xrightarrow{k_r} P_{ads} \quad \text{Reaction}$$

$$P_{ads} \xrightarrow{k_d} P_{gas} \quad \text{Desorption}$$

Bimolecular (one reactant adsorbed on catalyst surface, one gas phase)

$$A_{gas} \underset{k_{-a}}{\overset{k_{+a}}{\rightleftharpoons}} A_{ads}$$

$$A_{ads} + B_{gas} \xrightarrow[k_{-r}]{k_r} P_{ads}$$

$$P_{ads} \xrightarrow{k_d} P_{gas}$$

Bimolecular (both reactants adsorbed on catalyst surface)

$$A_{gas} \underset{k_{-a}}{\overset{k_{+a}}{\rightleftharpoons}} A_{ads}$$

$$B_{gas} \underset{k_{-b}}{\overset{k_{+b}}{\rightleftharpoons}} B_{ads}$$

$$A_{ads} + B_{ads} \underset{k_{-r}}{\overset{k_r}{\rightleftharpoons}} P_{ads}$$

$$P_{ads} \xrightarrow{k_d} P_{gas}$$

Industrial catalytic reactors

Although industrial catalytic reactors exist in a wide range of types, shapes and sizes, one method of categorizing them is by the size of catalyst particles. Large-particle catalysts are generally kept stationary, and the reaction mixture passes through the bed of particles. The particles are usually greater than 2 mm in size.

For small catalyst particles, the flowing reaction mixture suspends the solid catalysts, such that the solids behave like a fluid. The catalyst must be separated from the reaction mixture at the reactor exit. Particle sizes in this case are generally in the range from 10 µm to 1 mm.

Because most chemical reactions involve either heat being evolved or absorbed, one challenge in heterogeneous reactors is to maintain the optimal temperature within the catalyst bed and catalyst beads so that the catalyst is fully effective. ■

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2. Center for Industry Education and Collaboration, University of York, Catalysis in Industry, The Essential Chemical Industry, www.essentialchemicalindustry.org, 2013.

Epichlorohydrin Production from Propylene

By Intratec Solutions

Epichlorohydrin, (also known as ECH and chloromethyloxirane), is an organochlorine compound and a highly reactive epoxide that is widely used in the production of epoxy resins. Produced with purities of greater than 98%, epichlorohydrin is a clear, colorless liquid. At commercial scale, epichlorohydrin is mainly produced via chlorohydrination of allyl chloride, obtained in turn from the chlorination of propylene at high-temperature. Epichlorohydrin is mainly used in the production of bisphenol A, a raw material for epoxy resins, glycerol, and elastomers.

The process

The process under analysis comprises three major sections: allyl chloride reaction; propylene recovery; and epichlorohydrin (ECH) production. Figure 1 presents a simplified flow diagram.

Allyl chloride reaction. Initially, chemical-grade propylene is preheated, mixed with chlorine and fed to a reactor where the chlorination reaction is carried out. The reaction occurs in the vapor phase, generating allyl chloride and byproducts. The chlorination products are cooled and then directed to the prefractionator, where a stream rich in organic chlorides is separated from unreacted propylene and hydrogen chloride. The organic chlorides are routed to two distillation columns for the removal of light-end impurities and heavy-end impurities.

Propylene recovery. The distillate from the prefractionator is washed countercurrently with water in an absorber, in such a way that the HCl is absorbed. This process forms an HCl solution, which is removed from the column bottom. The gaseous stream from the overhead of the absorber is fed to a caustic scrubber, where residual hydrogen chloride is removed. The washed propylene gas is compressed in a multi-stage compressor and then recycled to the preheating stage.

Epichlorohydrin production. The allyl chloride stream is reacted with hypochlorous acid, formed in turn by chlorine dispersion in water. The chlorohydrination reaction is conducted in the liquid phase, adiabatically. The liquid product from this reaction is passed through a separator system, which separates the aqueous phase from the hydrocarbon phase. The aqueous phase, containing hypochlorous acid, is recycled, and the hydrocarbon phase, containing glycerol dichlorohydrins, is reacted with calcium hydroxide to yield epichlorohydrin product. The crude ECH stream is passed through one stripper and two distillation columns for the removal of calcium chloride, light-end impurities and heavy-end impurities.

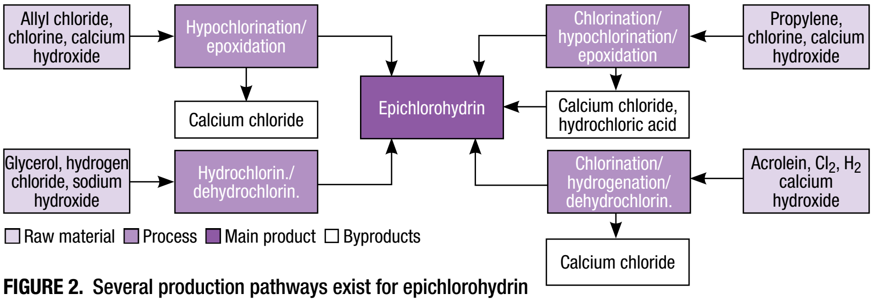

FIGURE 2. Several production pathways exist for epichlorohydrin

Production pathways

Epichlorohydrin is commonly produced from allyl chloride, derived from propylene. Production routes based on allyl alcohol and on the glycerol byproduct from biodiesel production have also been used. Different pathways for ECH production are presented in Figure 2.

Economic performance

The total operating cost (raw materials, utilities, fixed costs and depreciation costs) estimated to produce epichlorohydrin was about $1,850 per ton of epichlorohydrin in the second quarter of 2015. The analysis was based on a plant constructed in the U.S. with capacity to produce 80,000 metric ton per year of ECH.

This column is based on "Epichlorohydrin Production from Propylene – Cost Analysis," a report published by Intratec. It can be found at: www.intratec.us/analysis/epichlorohydrin-production-cost. ■

Edited by Scott Jenkins

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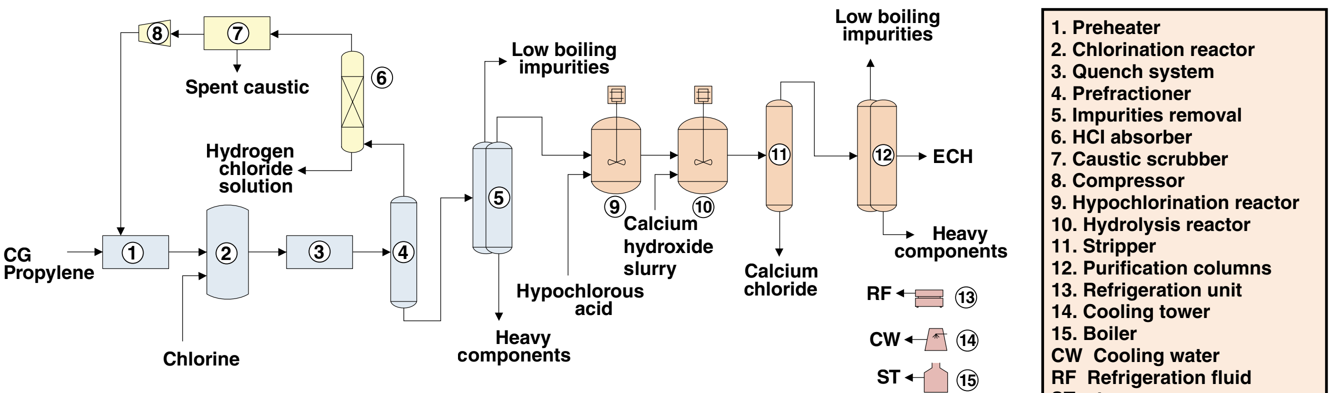

FIGURE 1. The diagram shows the production of epichlorohydrin from propylene and chlorine

Overcoming The Talent Dearth

A shortage of technical talent and experience is challenging many in the chemical process industries. Steps that can be taken to improve the situation are discussed

Carl Rentschler
Engineering Consultant
Goutam Shahani
ShureLine Construction

IN BRIEF

The changing professional climate and the vexing economic situation among technology-based companies are leading to a shortage of technical knowledge as compared to past years. This technical talent shortage can affect company performance, and cause companies to be less competitive than in the past. The reasons causing the change are varied, but include retiring technical specialists, the change in goals among young professionals, the shifting of work overseas and the lack of systems to capture historical "lessons learned."

FIGURE 1. The shortage of skilled workers is due to an imbalance in supply and demand

While there is no single solution to overcome the technical talent shortage, there are steps that can be taken to improve the situation. These include involving retired professionals as consultants, and within companies, instituting mentoring programs between technical experts and aspiring young professionals. In addition, knowledge management systems can be put in place to capture technical information, and progressively used to guide technical growth in a company. Elevating the career path of technical roles is a means of encouraging young engineers to focus on technical knowledge growth and become subject matter experts. While technical depth within companies may not reach the level of past years, there are ways to ensure that projects receive proper technical coverage. Another option is to form strategic partnerships with companies that possess the required technical skills and competencies. This article discusses different sides of the issue, and presents various alternatives that companies can pursue as a remedy.

Importance of technical depth

Competitiveness among design companies, and the need for operating organizations to immediately and creatively address problems, is making it more important than ever to have strong technical talent in these organizations. The design company that offers a unique and economical solution is generally the one that wins new business. For operating organizations, lost production time can quickly affect bottom lines, so having expert engineering talent available to immediately address problems is crucial. Solid designs are often a result of years of design changes with each succeeding change enhancing the durability and operability. This evolution can only be realized with core technical talent that has "lived" the changes, understands the nuances and has a keen mind for continual enhancements. Continual innovation within companies is a key differentiator in a challenging business world, and the best way to get there is to have solid technical talent.

The problem

There are several reasons why the shortage of technical talent has been exacerbated in recent years (Figure 1), but a main reason is that many "baby boomers" have been retiring, taking a wealth of technical

knowledge with them. These retiring engineers often grew their technical knowledge as advances were made in their respective technical areas. This provided them with in-depth knowledge and the ability to address problems based on experience. Most of the retiring engineers started their careers doing hand calculations with minimal technology aids, such as programmable calculators and computer programs (Figure 2). Following this path forced them to have a deep understanding of technical issues and then to grow their knowledge with exposure to problems and the addition of technology aids. Such a path does not exist today, and young engineers are often forced to "hit the ground running" with no mentoring, and have little choice but to use packaged programs.

The authors are acquainted with an octogenarian who was the last stop for technical problems at their previous company. He approached each problem with a yellow pad and pocket calculator, with occasional reference to a textbook. His huge technical depth allowed him to address the most daunting problems without sophisticated engineering computer programs, while providing unique technical and workable solutions.

FIGURE 2. Engineers develop expertise using traditional tools over decades

Lack of technical growth. In past decades, the technical expert in a company was a highly respected professional, and a person young people strove to emulate. This is generally not the case today and the most highly respected professionals in a technical organization are often those in the business side of a company. Technical growth is

FIGURE 3. Corporations need to create a climate where it is easy for young people to reach out to experienced people

often not recognized and rewarded. Consequently, young people often favor careers in business, marketing and finance. Technical positions are not viewed as "fast track" and today, quick forward movement is important to the young professional. Biding your time to become the best technical expert is not even a point of consideration for most technical professionals today. On top of this, the current trend is for engineers to switch jobs more frequently than in past years. The downside of this is that technical growth is not often continuous across job changes, and taking the masses of people switching jobs frequently, the overall technical growth in companies is diminished.

Overtaxed experienced workers. The current emphasis to cut costs in most organizations has resulted in experienced workers being overextended, with no time left to mentor and coach young professionals. In addition, the focus on cutting costs has led to a decline in training programs, both in-house and external. At the same time, attending conferences and participation in industry groups (such as the AIChE local chapter) are sometimes not supported by the corporation. Hence, young engineers are left on their own to develop professionally.

However, the best long-term solution is creating a culture where technical knowledge is valued, and companies strive to encourage and recognize individuals with a desire to be "best in class" in their technical field.

Education. Another reason for a lack of technical depth is that some studies have shown that schools are not adequately preparing students for engineering roles, and fewer students are graduating with engineering degrees [*1*]. The recent recession in the engineering profession may be a reason for more students not pursuing technical educations. With a shallower technical depth of engineers entering the workforce, mentoring becomes increasingly important. While larger companies may have the resources for shadowing, rotational programs and training, smaller companies often do not have the resources for such programs. Because engineers often have to "hit the ground running," they rely on computer programs that provide data-in and data-out, while the engineers sometimes do not have an in-depth technical understanding of the evaluation process and results.

Not capturing technical information. Coupled with shallower technical talent in recent years is the problem that most companies do not have a system to capture and share knowledge and experience of the more experienced (and often retiring) professionals. The authors have been exposed to "lessons learned" databases in their companies, but these are generally not maintained because of time limitations, and therefore crucial technical knowledge is not captured. The added problem is that captured information is often not viewed regularly and therefore opportunities to benefit from past technical gains are not realized. On top of lost technical gains, there generally are no formalized succession plans. Therefore, as more experienced engineers reach retirement age, "rules of thumb" and other key technical knowledge are not passed on to younger engineers.

Global competition. The tight commercial aspects of U.S. projects has often driven companies to seek less expensive engineering overseas. Known as High Value Engineering Centers (HVECs), these companies are prevalent in countries such as India, China and the Philippines, and offer U.S. engineering, procurement and construction (EPC) and owner-operator companies the

opportunity to save considerable money on engineering costs associated with major projects. A downside of this approach is that the technical knowledge gained in executing projects is moved overseas, and U.S. companies have less opportunities to benefit from design experience. Over time, this will lead to further diminished technical knowledge in the U.S. and the possible need to engage foreign companies to address emerging problems.

Construction talent. While the focus of this article so far has been on engineering knowledge, the same issue with declining talent applies to the construction trades. Even though the construction industry may not be booming as in recent years, still there is insufficient skilled labor in many trades. The younger generation has generally been pushed toward college and not toward the vocational trades. Therefore, this has left a serious gap in construction capabilities, and often leads to construction inefficiencies [2]. Finding acceptable and sufficient construction talent is one of the major challenges facing construction and EPC companies. Some of the steps that are being considered include the following:

- Promote vocational training in schools
- Offer competitive salaries and benefits
- Provide advancement opportunities within a company (For example, promote welder to construction manager)
- Provide cross-training, including estimating and proposal development to field personnel

Possible solutions

Some possible solutions to the impending problem of a lack of technical talent are discussed here.

Take advantage of experienced personnel. Experienced technical professionals in the age group of 50–70 have a lot to offer. This includes experience gained over decades in a variety of companies and projects and spanning multiple technical functional disciplines. The perspective gained from real-world experiences, coupled with strong technical fundamentals, provides a formidable combination, which cannot be replicated by computer programs. There is also a natural tendency on the part of experienced people to pass on their knowledge to the younger generation. Corporations need to create a climate where it is easy for young people to reach out to experienced people (Figure 3). This interaction can be facilitated by having people co-located, an open door policy and the availability of some spare time so that employees never have to make a choice between completing a project versus teaching a younger professional.

Engage retired people on a temporary basis. As noted earlier, people who worked long-term have significant technical knowledge into which to tap. A win-win option for a company and retired person is to establish an hourly contract, allowing the company to call on the technical expert as needed. This is an economical option because the retired person is paid only when working, and this option provides easily accessible technical knowledge on short notice. For the retired person, there is an opportunity to stay engaged on a part-time basis, and earn some modest income.

Employ knowledge management. There are numerous computer programs that capture, organize and maintain detailed technical reports and calculations. It is relatively easy to classify and organize reports in such a way to make searching relatively easy. The challenge is to create a culture where knowledge management is valued and information exchange is the norm. This capability is especially important in a large, multinational company that is project driven. In such organizations, the project team usually disperses after completion of a project. The lessons learned and best practices developed usually also get dispersed unless a conscious effort is made to capture and use that knowledge.

Increase training. In the recent past, it was typical for large tech-

nology-based companies to encourage employees to dedicate two or three weeks annually to formal technical and skills training. It was quite common to attend one or two technical conferences. This meant young professionals could interact with others in industry, develop a professional network and develop leading-edge skills at the same time. The costs were not scrutinized and the benefits were assumed to come from employees being more satisfied and productive in the long run. This training was integrated into the annual performance plan and employees were measured on how well they completed their training.

Taking steps to capitalize on experience within a company is a needed process to ensure that technical depth is not lost.

Make technical career paths more rewarding. Many large technology companies have created a technical ladder where a senior person can have the same prestige, salary and benefits as other executives without having to manage a large budget or a large number of people. Such an arrangement encourages professionals to dedicate their career to a technical specialty instead of gravitating toward a business or finance role that carries better rewards.

Form strategic partnerships. Sometimes it is better to form a strategic partnership with a company that has the required technical knowledge base as a core competency. A good example is the strategic partnership formed by Air Products (operating company) with Technip (engineering company) in HYCO plants. Such a partnership can be a win-win, enabling both companies to prosper and build differentiation in the marketplace.

The bottom line

The changing times are leading to a situation in which growing and maintaining technical depth in an organization is challenging. Many very experienced engineers are retiring, and often there is no backup for the lost talent. With a current focus on fast-track advancement, young professionals are often driving their careers toward the business side of a company. In cases where technical growth is sought by young professionals, there generally are no mentoring or training programs in place to capitalize on the available knowledge. On the construction side, skilled craft is also in short supply as young people have been steered away from the trades. Definite steps are necessary to ensure that engineering and construction talent is developed to support projects and operating facilities, plus long-term company growth.

Taking steps to capitalize on experience within a company is a needed process to ensure that technical depth is not lost. This means that experienced engineers are encouraged to mentor young engineers, and young engineers are encouraged to proactively seek out the knowledge. Also, creating technical career paths within a company is a means to reward people desiring a technical path over a business/management path. Calling on retired technical experts is one means of quick relief for the talent drain, and also forming strategic partnerships is another approach. However, the best long-term solution is creating a culture where technical knowledge is valued, and companies strive to encourage and recognize individuals with a desire to be "best in class" in their technical field. The outcome will be more technically respected companies and professionals with a renewed eye toward the technical side. ■

Edited by Dorothy Lozowski

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A Concise Guide to IBCs

When properly selected and stored, intermediate bulk containers (IBCs) can be used to safely transport products in the chemical process industries

Kevin Kling
Greif, Inc.

IN BRIEF

Demand within the global market for rigid intermediate bulk containers (IBCs) has grown at a steady rate in recent years with the rising need to transport liquids, such as food, fuels, chemicals and hazardous materials. Chemical and pharmaceutical industries are the major end users of IBCs, with growing investment in the chemical industry being a contributing factor in the increase in demand.

A major growth driver in the IBC market is the cost-effective transportation and storage, ease of maintenance, and reusability afforded by this industrial packaging type. IBCs are particularly suited to the chemical industry, as they can safely transport a variety of solid or liquid products, including materials requiring safe handling, as well as those identified as hazardous or dangerous.

FIGURE 1. IBCs come in a variety of sizes and materials of construction. The one shown here is designed for maximized space, and can be stacked, depending on the weight

The main properties of IBCs

IBCs are rigid, self-standing vessels made from metal, fiberboard or plastic material (Figure 1). The typical volume is 275 gal although there are specialty versions available ranging from 119 up to 793 gal. The construction typically consists of a base pallet with a bulk tank attached. The most widely used IBCs within the chemical industry are those with a bulk tank or bottle made from plastic material — typically a high density polyethylene (HDPE) — which is then protected by a durable galvanized outer steel frame. The bulk tank usually includes a fill port with a cap along with a valve for emptying. There may also be requirements for service equipment, such as a pressure-relief valve when filling substances such as organic peroxides or products that are filled at high temperatures.

Packaging standards and symbols

IBCs must be manufactured to adhere to strict standards in order to ensure the integrity of the product. These include U.S. Food and Drug Administration (FDA) compliance for plastic resins and additives in 21 CFR, religious requirements for Kosher and Halal, no deleterious substances in the materials of construction, REACH (Restriction, Evaluation, Authorization and Restriction of Chemicals) compliance, and U.S. Dept. of Transportation (DOT) performance packaging).

The packaging symbols on an IBC are an important consideration when looking at the storage and transportation of chemicals. There are two symbols used to denote the type of chemicals that can be stored in an IBC; UN and Non-UN. If an IBC is embossed with the letters “UN”, it is suitable for storing hazardous goods, such as corrosive chemicals. IBC tanks that have a “Non-UN” approval are suitable for non-hazardous bulk chemical storage only.

FIGURE 2. IBCs can filled with various products

The key advantages of IBCs

There are several key advantages of using IBCs over chemical drums including the following:

Efficiency of space. IBCs maximize the volume of liquid chemicals that can be stored in a given space compared to drums. For example, a 275-gal IBC has the equivalent volume of five 55-gal drums in the space of four.

Ease of movement. Due to the integrated pallet, IBCs can be loaded and unloaded with the use of a forklift, thus saving valuable time (Figure 2).

Easy discharge. The discharge port and valve allows most users to empty simply by the use of gravity, making them easier to use and eliminating waste.

Durability. IBCs offer higher stress crack resistance than standard plastic drums.

Visibility. Users can see content levels (typically this is not possible with a standard tight head drum due to the thickness and color).

Returnable or recyclable. IBCs offer a sustainable solution for storing chemicals because they can be refurbished and when they have come to the end of their service life, they can be recycled into other products.

Environmental efficiency

While each of the above advantages are important, the increased demand for returnable or recyclable packaging from various end-use industries has been a key driver for the IBC market growth in recent years. This is expected to continue as more companies develop sustainability goals.

In fact, the IBC segment of the returnable packaging market is one of the highest in terms of volumes recycled. The growth of this segment can be attributed to the high strength and durability offered by IBCs, properties that allows for multiple life cycles. In addition, the construction allows for the replacement of a damaged sub-component to extend the life of the overall package.

IBCs returned for reconditioning must be subject to stringent inspections that take into consideration important factors such as the type of product that has been stored in the IBC, and any UN or non-UN markings. Any chemical residue must first be neutralized before reconditioning can take place. The first step in the IBC reconditioning process involves a visual check of the outer structure and any necessary repair work. The IBCs are then cleaned and rinsed. After this they are dried and undergo rigorous seal and leak testing, with all valves, gaskets and closures repaired or replaced as necessary.

Similar to reconditioning, there is also the option to rebottle an IBC. In this instance, the cage gets cleaned, however a new bottle gets inserted for use. The previous bottle is generally rinsed then ground up and often that plastic gets repurposed into IBC feet and other industrial products.

Product compatibility

IBC suppliers will assist in the selection of the correct type of IBC for various products. However, ultimately, the suitability of the IBC for the intended filling product is the responsibility of the user.

Before an IBC is used for the transport of dangerous goods, its chemical compatibility with the filling substances must be sufficiently verified, therefore users must consider whether regulations authorize the use of the IBC for the material to be transported. Factors such as the physical characteristics of the materials and specific requirements around filling, transport, storage and emptying must be assessed. Gasket compatibility and the compatibility of service equipment also need to be considered. Supplying precise specifications regarding the product to be packaged will enable the supplier to recommend the correct IBC to meet the requirements.

Depending on the material to be carried, the use of a composite IBC with a permeation-resistant barrier layer may be recommended. Permeation defines the temperature-dependent mass transfer through solid material, especially plastic. A permeation-resistant barrier layer can minimize the permeation of a substance outwards. It may also prevent inward permeation of molecules such as water, oxygen and other gases. Permeation barriers can be achieved through different technologies, including the use of additives or fluorination.

Filling and emptying IBCs

A three-step procedure is recommended for the filling process.

1. Prior to filling, inspect the IBC to make sure that it is in good condition and ensure the outlet valve is closed.

2. Fill the product through the top fill port at atmospheric pressure, not exceeding a temperature of 70°C (~158°F), depending on the design type. IBCs are not designed for pressurized filling.
3. Ensure that there is sufficient venting of the bulk tank or bottle as it cools to prevent vacuum deformation.

Due to the wide variety of valves and caps, it is necessary to request the specific closure instructions from the IBC manufacturer for each component and ensure they are torqued to the proper specification.

Before emptying, open the top lid and vent the bullk tank to prevent vacuum collapse and empty through the lower outlet valve. If using a pipe or pump, make sure that it is independently supported and does not touch the outer frame, as this can cause vibrations that can damage the inner bulk tank.

Storage and transportation

The following guidelines ensure best practice for storage and transportation of IBCs.

- When using a pallet jack or forklift to move IBCs, always ensure the forks reach all the way underneath the pallet
- Properly secure all IBCs to prevent movement and damage during transit
- Check the UN marking on the IBC's identification plate for its stacking test load to ensure it can be safely stacked
- Proper nesting is critical — always two on two, not one on three
- During transport, only stack IBCs two layers high

IBC stacking guidelines

Storage methods, conditions, and ladings can impact the stacking performance of IBCs therefore the following should be used as a guide only (Figure 3).

- IBCs containing ladings with a specific gravity of 1.5 or less can be stacked to a maximum of three high
- IBCs containing ladings with a specific gravity between 1.5 and 1.8 can be stacked to a maximum of two high
- Stacking IBCs containing ladings with a specific gravity above 1.8 is not advised

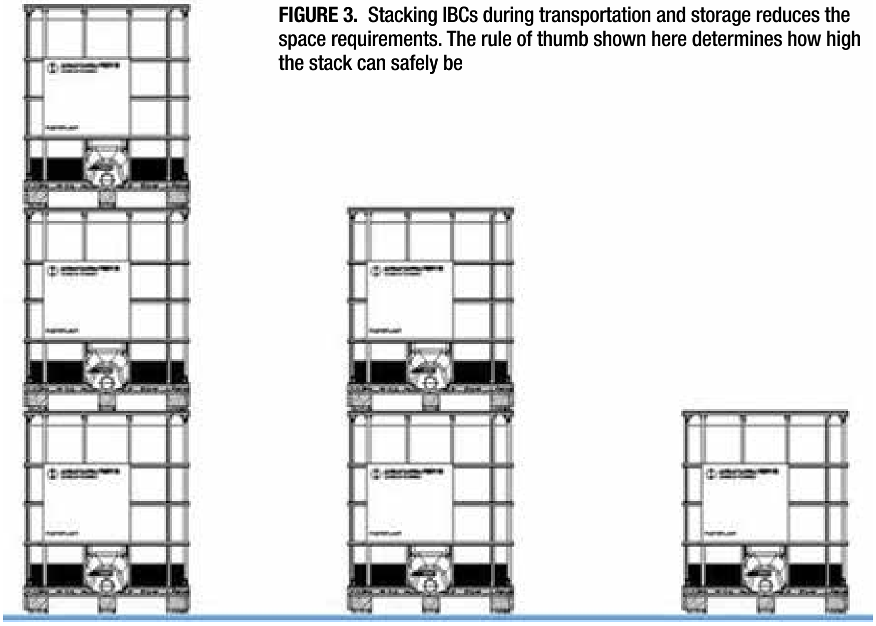

FIGURE 3. Stacking IBCs during transportation and storage reduces the space requirements. The rule of thumb shown here determines how high the stack can safely be

The stacking mark explained

As of January 1, 2011, all IBCs authorized to transport hazardous materials feature a sticker highlighting the unit's maximum top load during transport. This recommended stack value should not be exceeded. The symbol is required to be no less than 100 mm × 100 mm, be durable and clearly visible. The mass marked above the symbol must not exceed the load imposed during the design type test divided by 1.8.

Developments and innovations

Some exciting developments are happening within the IBC market, albeit more gradually than in other areas of packaging. These include innovations such as improved barrier protection within the bulk tank that offers greater product stability, shelf-life and operational performance. Users benefit from a longer product shelf-life, a reduction in harmful air pollutants coming from their product and increased protection of their product against oxygen permeation from outside the container. Also, improvements to sealing equipment, such as branding on seals to remove the risk of product counterfeiting and improved product protection.

Innovation and investment remain as essential as ever. Industries will continue to see increasing pressure to reduce waste and limit resource use, and therefore packaging will continue to become smarter to ensure these requirements are met.

However, although minimizing the environmental impact of packaging is a priority, when implementing sustainable practices, the challenge that the chemical industry will face is that companies must always ensure they are not compromising safety, particularly when dealing with hazardous materials. ■

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Part 2

Selecting, Handling and Maintaining IBCs

A number of factors are involved in selecting the right intermediate bulk container (IBC). An overview is presented here

Uwe Bartels
Hoyer Group

IN BRIEF

SAFETY DATA SHEETS

SELECTION CRITERIA

MAINTENANCE AND CLEANING

An intermediate bulk container (IBC) is a large package for transporting chemicals into a plant or products from the plant. IBCs display different properties and must fulfill various functions. The selection of a suitable IBC to transport a particular product must always be determined based on the properties of the goods to be conveyed. The type of IBC that is used can be determined according to the requirements of the substances and mixtures involved. That means the properties and requirements of a chemical or product will specify both a container's quality and the associated equipment (Figure 1).

FIGURE 1. IBCs come in a variety of sizes and shapes, and can have additional equipment attached, such as valves and couplings

The numerous characteristics that various products may show yield a series of criteria that must be examined carefully before selecting the correct IBC. One important example is the product's toxicity and its general environmental risk. The requirements that a package must fulfill can be defined based on these properties. Based on them, either an appropriate standardized IBC model can be chosen, or it is possible to develop an individually customized solution corresponding to a specific product's requirements. This allows goods to be transported to their final destination safely and securely.

The potential risk — the law talks about degree of hazard — that can emanate from a product determines the material of construction. An IBC can be made of plastic, stainless steel or some other material, such as paper or composite material.

Safety data sheets

Speaking about product properties leads immediately to the product safety data sheet (SDS). This important data sheet is defined by Article 31 and Annex II of (EU) Regulation 1907/2006 (the REACH Regulation), in conjunction with the provisions of the European Chemicals Agency (Guideline for Preparing Safety Data Sheets), possibly together with other national regulations, such as TRGS 220 (Technical Rules for Hazardous Substances) in Germany. The SDS contains all the safety-related information about substances and mixtures being transported or handled. In addition to safety-related information about products, the SDS also contains handling recommendations on the basis of which it is possible to take the actions required to protect health, for workplace safety and to protect the environment. In E.U. member states and in many other countries, a supplier, importer and manufacturer of substances and mixtures classified as dangerous must provide a SDS. The author of the SDS must take care to ensure that it contains all the information about the hazards of a substance or a mixture, together with information about its safe storage, handling and disposal. It is es-

sential that this information is available when specifying and selecting a suitable IBC.

Selection criteria

A whole series of additional considerations must be taken into account when selecting an IBC, including testing the product's compatibility with the IBC's material of construction, as well as the specific gravity of the product, its viscosity and its requirements in relation to the package's geometry. These involve its flow properties during filling and/or emptying.

Legal issues. Many different regulations apply to the handling of large packages, such as IBCs (for example the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR)).

To obtain an overview of legislative changes, it is absolutely essential to observe the constantly changing legal provisions and to continuously re-examine products to determine whether they are suitable for transport in an IBC.

Almost all users now employ a wide variety of databases, although these can only be as good as the maintenance of their contents or updating of changes or innovations.Taking these parameters into account yields a selection of suitable — and legally permissible — IBCs.

Added to this is the need to make sure that the dimensions or connections are compatible both for the organization doing the filling and for the recipient organization.

Sizes. The spectrum of different IBC types is highly diverse, so it is scarcely possible to present a total overview. However, certain volume categories have evolved, and these are customary in markets worldwide. Various differently designed containers in the 500-, 800- and 1,000-L volume classes are often used. Larger units are to be found in the market slightly less often. The reasons for this include their greater weight and the associated challenges when handling them. Therefore a tank container or road tanker is a more suitable means of transport when conveying rather large volumes of liquids, whereas a silo truck offers advantages for goods in powder form.

Geometry. Another distinguishing feature is the shape of the IBC. As a rule, a distinction is drawn between cube-shaped solutions and cylindrical containers. Both offer advantages and disadvantages, depending on the deployment scenario, for example, in relation to cleaning or the ability to stack them. An advantage of cylindrical IBCs is that they are easier to clean, whereas cube-shaped containers are easier to stack on a truck due to their shape. In the latter case, it means that larger volumes can be transported as a result.

In addition to the standardized IBC types offered by various manufacturers and leasing organizations, specially tailor-made designs are also developed for quite specific products in order to exactly meet the needs of the goods and the user. Temperature-controlled containers with heating or cooling systems are often fabricated for special product requirements.

Inspection. Furthermore, containers must always be in-

FIGURE 2. All IBCs need to be inspected for external and internal damage before being used

spected for external or internal damage before being used (Figure 2). Additional safety examinations should also be carried out if special solutions are used for heating with electrical energy, hot water or steam. The same applies when using IBCs that can be cooled, or when using auxiliary mixing and stirring solutions (internal or external agitators).

Hazardous areas. Special care is advisable when using IBCs in areas where there is an explosion danger. Special ATEX (Equipment Intended for Use in Explosive Atmospheres) solutions are available on the market and offer increased safety for personnel, products and the environment.

Handling. Whichever type of IBC is suitable for the product, the container should always be operated and used by specialist personnel and/or based on proper instruction and complete operating instructions. This can prevent accidents and damage to the equipment and to the product being transported. When handling IBCs, it is absolutely essential to ensure that the containers are transported or lifted using approved conveying equipment. Incorrect handling or exceeding the permissible total weight can cause damage to the transport equipment and subsequently to the product. Based on design differences, IBCs with an almost identical design are approved for different total weights. In most cases, these distinctions are not visible purely externally. The only thing that gives reliable information about the permissible total weight is the identification marking, known as the type plate, which is a mandatorily required identification and is attached to the IBC.

The following information is affixed permanently and in a clearly readable manner to the type plate of every IBC:

- Manufacturer's name and address
- Type description or series name
- Year of manufacture
- Manufacturing number
- Container number
- Tare weight
- Tank construction material
- Filling and emptying pressure
- Volume
- UN Number
- Test data

Before every use, a container must be grounded (earthed) against electrostatic charge, and venting must be ensured both during filling and during emptying. The most common sources of error include incorrect connection to a pipework or hose system and incomplete closing of fittings or failure to check the filling level, or both.

Maintenance and cleaning

Another absolute necessity is that arrangements must be made for cleaning, repairs and maintenance works to be carried out by appropriately qualified specialist personnel. Depending on the product, a large variety of different preparation and cleaning steps are necessary. The SDS provides information about the product's properties. The safety of the personnel and the avoidance of unwanted chemical reactions and the avoidance of escapes of product with negative impacts on the environment have topmost priority. The IBC must be clearly identified, and product residues that may possibly be present must be emptied out. Only then can the actual process of cleaning the IBC take place. Here again, various steps are necessary, such as selecting a suitable cleaning medium, defining the type of cleaning, choosing the cleaning additives, specifying the cleaning temperature and so on. The measures that are required also depend on the container's level of contamination.

Depending on their approval, IBCs must be subjected to tests, inspections and maintenance at regular intervals. The statutory regulations can be found in the ADR, Chapter 6.5, Construction and Testing Regulations for Large Packages (IBCs). Special attention must be devoted to compliance with time limits/intervals and documenting the testing/inspection (in addition to the certificates) in such a way that valid documents can be produced at any time.

As a rule, the administration of all the container information with regard to the use of the IBC is dealt with by trained personnel. Database-assisted software is almost always used to administer a container. The complexity lies in the interaction between the individual factors: the product and its properties, the choice of a suitable IBC, and the IBC's filling and transport, emptying, cleaning, servicing and reuse and storage. This turns what is actually a simple large package into a product that is complex when being used. ■

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Cooling Towers: Water-Treatment Options Advance

Water-treatment programs for cooling towers have evolved in recent years, favoring non-phosphorus programs today. This article reviews the impact on water chemistry and operating reliability

Brad Buecker and Ray Post
ChemTreat

Cooling towers are a critical component of many industrial facilities. Cooling towers evaporate only pure water, forcing the minerals in the water to progressively concentrate, or "cycle up." The enriched mineral content makes the water more corrosive and can lead to the deposition of sparingly soluble salts, such as calcium carbonate, on critical heat-transfer surfaces. The resulting design and operating challenges have become particularly acute following the gradual phase-out of chromate-based treatment programs (beginning in the 1970s) due to human health concerns. However, the most widely used replacement programs, whose core chemistry is based on the use of inorganic and organic phosphates, has proven to be less effective and much more difficult to control than the earlier chromate-based corrosion inhibitor programs.

Today, with phosphorus discharge to receiving bodies of water being restricted (or even banned in some places), ongoing effort is underway to find suitable alternatives, with movement toward treatment programs that do not contain phosphate or zinc. Like any major change, acceptance comes slowly until plant personnel understand the performance benefits of the new technology. This article examines the ongoing evolution in water treatment for cooling towers.

The 'good old days'

Cooling systems typically have mixed metallurgy, with carbon steel being the common economic material choice for system piping, heat-exchanger shells and even tubes. Where greater corrosion resistance is required for heat-exchanger tubes, stainless steels are often the choice material used today. This includes the venerable Types 304 and 316, as well as the newer Duplex grades, UNS 2205 and UNS 2507.

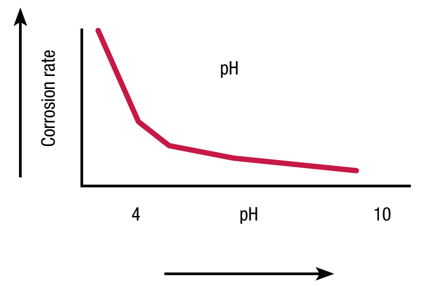

FIGURE 1. This graph shows the general influence of pH on the corrosion rate of iron and copper

Copper tubes are widely used for chillers, with both the inner diameter and outer diameter textured to improve heat transfer. Admiralty brass and copper-nickel alloys are still used for heat-exchanger tubing, due to their chloride resistance, although titanium and super-ferritic stainless steel are becoming more popular for applications that require high reliability in cooling waters that have a high chloride content.

Chromate was such a powerful corrosion inhibitor that it enabled cooling systems to be operated at a lower, more corrosive pH, typically in conjunction with sulfuric acid for pH control. This chemistry is quite straightforward. In most natural waters, and especially when progressive cycling causes water constituents to become concentrated inside a cooling tower, the primary water chemistry issue (apart from microbiological fouling) is calcium carbonate ($CaCO_3$) scale deposition, as shown in Equation (1):

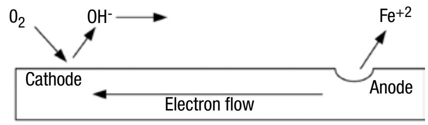

FIGURE 2. In an aerated-water corrosion cell, iron dissolution and metal loss occur at the anode while oxygen reduction occurs at the cathode

$$Ca^{2+} + 2HCO_3^- + heat \rightarrow CaCO_3 \downarrow + CO_2 \uparrow + H_2O \qquad (1)$$

The equation illustrates the inverse solubility of $CaCO_3$ as a function of temperature. As cooling water temperature rises inside heat exchangers, the exchanger tubes or plates become susceptible to $CaCO_3$ deposition. The historic acid-chromate program inhibited scaling by reacting sulfuric acid with bicarbonate ions (HCO_3^-) to convert the ions to CO_2, which then escape as gas. A typical pH control range was at or near 6.5.

The second compound in the formulation, sodium dichromate dihydrate ($Na_2Cr_2O_7 \bullet 2H_2O$), provides hexavalent chromium ions that react with carbon steel to establish a protective pseudo-stainless-steel layer.

Acid-chromate programs performed extremely well in most applications. Chromate programs were not only effective on steel alloys, but were also effective corrosion inhibitors for copper alloys. Chromate also has the advantage of being non-fouling. This allowed the flexibility to always feed an effective chromate concentration, even in highly corrosive waters and brines.

Goodbye chromate

The phaseout of highly effective chromium due to environmental and health concerns necessitated that cooling programs be operated under

less corrosive, higher pH conditions, as illustrated in Figure 1.

A typical formulation would include inorganic ortho- and poly-phosphate, an organic phosphate (aka phosphonate), a high polymer dosage to hold the phosphate in solution, and perhaps a small concentration of zinc. Several factors in such formulations are important to optimize both scale and corrosion inhibition. A brief review of some fundamental aspects of corrosion is provided below.

Corrosion is an electrochemical process, although erosion-corrosion also involves mechanical factors. A typical corrosion cell is shown in Figure 2, with the anodic reaction Equation (2) and cathodic reaction (Equation (3) shown below.

As is true for all electrochemical reactions, a circuit must be established for the reaction to proceed, and the anodic reaction and cathodic reaction must proceed at the same rate. In this example, each iron atom gives up two electrons at the anode and the iron ions at the surface dissolve into the solution, as shown in Equation (2):

$$2Fe \rightarrow 2Fe^{2+} + 4e^{-} \qquad (2)$$

The electrons flow through the metal substrate to the cathode, where they reduce common species in the water. In typical cooling-system waters, the primary reductant is oxygen, as shown in Equation (3):

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \qquad (3)$$

The ions formed at the anode and cathode migrate toward each other, completing the circuit. The overall corrosion reaction is shown in Equation (4):

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2 \qquad (4)$$

This reaction can cause intense pitting in carbon steel. Also, ferrous hydroxide [$Fe(OH)_2$] will further oxidize to ferric hydroxide [$Fe(OH)_3$] and eventually become rust ($Fe_2O_3 \bullet xH_2O$) that can form heavy deposits and even close off small diameter pipes (Figure 3).

Water-treatment corrosion inhibitors are designed to slow down either the anodic or cathodic reactions, or both. While the old chromate treatment option was technically an anodic inhibitor, correct application would allow the chemistry in the system to establish the formation of a continuous, pseudo-stainless-steel layer on carbon steel.

Now, consider the more complex chemistry of the phosphate/phosphonate-based replacement programs. The list that follows outlines, in general, the function of the main compounds within a typical formulation:

- Ortho-phosphate (anodic/cathodic corrosion inhibitor)
- Poly-phosphate (cathodic corrosion inhibitor)
- Organic phosphates (calcium carbonate scale inhibitor and cathodic corrosion inhibitor)
- Polymer (calcium phosphate scale inhibitor)
- Zinc (cathodic corrosion inhibitor)

FIGURE 3. Shown here is a section of pipe that has become nearly closed off by iron oxide deposition

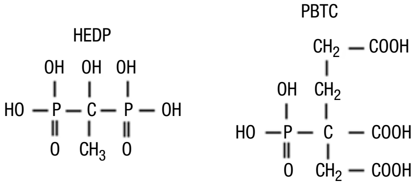

FIGURE 4. This figure shows two common phosphonates, 1-hydroxyethylidene-1,1-diphosphonic acid (HEDP) on the left, and 2-phosphono-butane-1,2,4-tricarboxylic acid (PBTC) on the right. Sometimes other compounds known as phosphinates may be effective

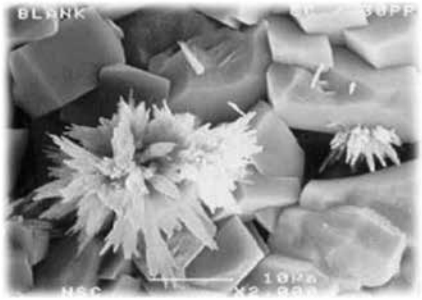

FIGURE 5. The deposition of crystalline mineral deposits on equipment systems can wreak havoc in an untreated cooling-water system

- Azole (corrosion inhibitor for copper alloys)

One early treatment method was based on a feed of phosphates, either ortho-phosphate (PO_4), or phosphate compounds that would revert to ortho-phosphate, to precipitate calcium as [$Ca_3(PO_4)_2$]. These programs also provided corrosion protection, as phosphate will react with ferrous ions (Fe^{+2}) produced at anodic sites to form a rate-limiting deposit, while [$Ca_3(PO_4)_2$] precipitates in the local alkaline environment at cathodic sites to inhibit electron transfer.

However, even small upsets in phosphate programs can cause severe calcium phosphate fouling, and in fact, $Ca_3(PO_4)_2$ deposition can become almost as great a problem as calcium carbonate scaling. Accordingly, treatment methods have continued to evolve to more-forgiving methodologies, where in many cases the backbone of these programs are the organic phosphates (phosphonates; Figure 4) with a supplemental polymer to sequester and modify the crystal structure of scale-forming ions and compounds. Phosphonates attach to deposits as they are forming and disrupt crystal growth and lattice strength.

A common treatment program might include one or perhaps two of the phosphonate compounds in low-mg/L dosages for primary scale control, with 5–15 mg/L or so of ortho-phosphate for additional scale control and corrosion protection, and perhaps 0.5 to 2.5 mg/L of zinc added, as well. Zinc reacts with hydroxyl ions generated at cathodes to form a precipitate [$Zn(OH)_2$], which provides additional cathodic protection. Also typically included in this formulation is 5–10 mg/L of organic polymer for control of calcium phosphate deposition.

It should be noted here that although chromate has disappeared as a treatment option, sulfuric acid feed to reduce alkalinity has remained quite viable, and continues to be utilized in many applications. Reduction of the calcium carbonate scaling potential by acid feed helps to reduce the load on the scale inhibitor and allow higher cycles of concentration and better water utilization efficiency.

When crystals of calcium carbonate, calcium phosphate, a silicate, or other species form, they create tenacious layers on the metal surface, impeding heat transfer efficiency and creating other operating issues. Treatment polymers interrupt crystal formation, producing deposits that remain non-adherent and are more easily removed

Careful monitoring and control of phosphonate-based programs is necessary, because overfeed of phosphonates can lead to calcium-phosphonate deposition. Additionally, phosphonates exhibit varying degrees of susceptibility to breakdown to ortho-phosphate from thermal and chemical stresses, particularly from oxidizing compounds. Degradation of the original phosphonates to ortho-phosphate will, of course, reduce the effectiveness of the phosphonates, and will also increase the ortho-phosphate concentration and potential for $Ca^3(PO_4)_2$ deposition.

Non-phosphorus options

Increasing concern with respect to the impact of phosphorus on the environment — in particular, its role in promoting harmful algae blooms in natural bodies of water — has driven demand for non-phosphorus (non-P) chemistry options for treating cooling-water systems. Also factoring into this evolution is the desire to reduce the discharge of zinc, due to its toxicity to aquatic organisms. The best of these non-phosphorous and non-zinc programs now offer important performance advantages, including reduced fouling tendency and better corrosion inhibiting performance in challenging waters.

The original polymers developed for scale control contained only carboxylate functional groups (COO^-), where the negatively charged oxygen atoms bind with calcium to modify crystal growth. More advanced compounds such as co- and ter-polymers have structures that may include carboxylate, amide ($R\text{-}CO\text{-}NH_2$), sulfonic acid (SO_3H) and nonionic groups for improved performance and resistance to degradation. These enhanced polymers have been formulated to help control other deposition, including calcium phosphate, calcium sulfate, iron hydroxide, magnesium and calcium silicates, manganese, and calcium fluoride, to name some of the most prominent.

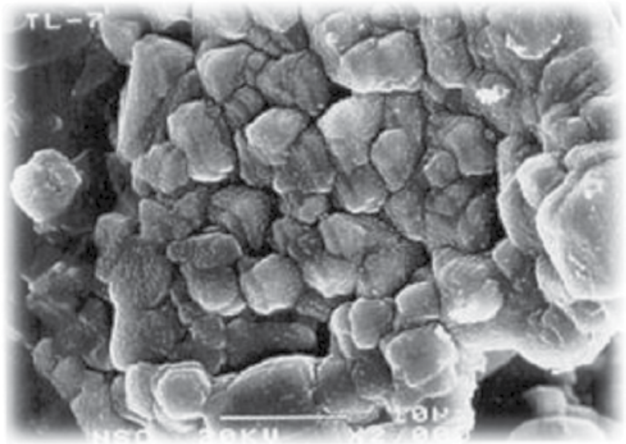

FIGURE 6. When treatment polymers are used, crystals are smaller, irregular, and remain non-adherent, allowing them to be washed away more easily

In the absence of any treatment, most minerals will deposit as well-ordered crystals on the surfaces of heat exchangers and other cooling system components, hindering efficient heat transfer (Figure 5).

Such crystals, whether they are calcium carbonate, calcium phosphate, a silicate, or some other species, usually form very tight and tenacious layers on the metal surface, impeding heat transfer efficiency and creating other operating issues.

In large measure, treatment polymers function by interrupting crystal formation; specifically the chemicals distort and interrupt the regular, orderly crystal building block process, producing deposits that remain non-adherent (Figure 6).

These loose materials are more easily washed away. Some polymers also act as sequestering agents, where negatively charged functional groups will bind with cations to prevent them from forming scale. An advantage of polymer chemistry is that each polymer chain can contain many functional groups. Thus, a common range for polymer concentration in the cooling water is 2 to 10 parts-per-million (ppm). To use an old saying: “A little bit goes a long way.”

But another important question remains: How effective is a non-P program for corrosion inhibition? In the first place, non-P treatments, like phosphate/phosphonate programs, have been designed to operate at an alkaline pH range (7–9), which tends to minimize general corrosion of metals. Even so, corrosion cells can still develop in an alkaline environment (Figure 7).

The key is a reactive polyhydroxy starch corrosion inhibitor (RPSI) that binds directly to the metal surface, unlike phosphate chemistries that must react with calcium to form a protective layer. The RPSI complex is independent of calcium, pH, or other water chemistry constituents [*1*]. This makes the program more forgiving than phosphate and zinc programs, which require precise control of system chemistry to prevent fouling on heat transfer surfaces. The non-fouling nature of the RPSI complex allows it to be dosed to provide the required level of corrosion protection (Figure 8).

Full-scale application of this new chemistry option has proven to be very effective. In one application,

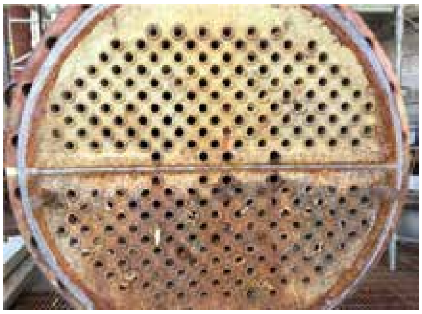

FIGURE 7. This two-pass heat exchanger that is using a zinc-phosphate program shows corrosion on the colder inlet pass, and fouling on the hot outlet pass

at a large industrial complex in the southeastern U.S., RPSI replaced previous polyphosphate and then zinc chemistry (Figures 9 and 10). Carbon steel corrosion rates have been reduced from 0.2–0.25 mm/yr to 0.0025–0.0075 mm/yr.

On a secondary note, the change from zinc and then to RPSI was in part influenced by problems with severe algae formation in a clarifier and recycle pond at the plant. The removal of phosphate from the water effectively addressed that challenge, allowing a 70% reduction in sodium hypochlorite (bleach) usage for microbiological control.

In another example, also at a large chemical plant, traditional phosphate chemistry proved satisfactory for corrosion control, but calcium phosphate deposits caused fouling in some of the plant's plate-and-frame heat exchangers. Such exchangers are notorious for low-flow locations and deposit accumulation. Conversion to RPSI chemistry maintained excellent corrosion protection and eliminated phosphate deposition (Figure 11).

One of the industries for which this newer chemistry option can be quite effective is power generation, where most plants are no longer base-loaded but instead operate in a cyclical (on and off) manner as part of normal operation. It is critical that a protective barrier be maintained on all cooling system metals in such applications, otherwise severe localized corrosion may result.

Power plants generally directly discharge their cooling water, and consequently face significant restrictions on the use of phosphorous and zinc corrosion inhibitors.

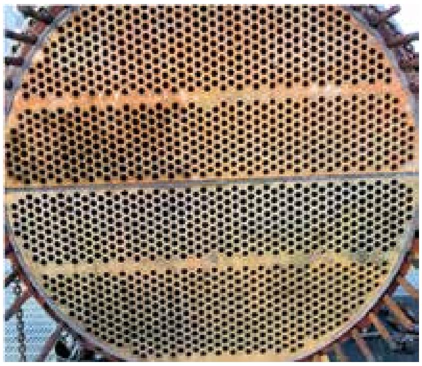

FIGURE 8. This four-pass heat exchanger that is using the RPSI corrosion inhibitor program shows no corrosion or fouling

Modern control methods

As with the other technologies, chemical feed and control capabilities have been vastly improved [*2*]. Automation of chemical feed and chemistry monitoring systems can do the following:

- Reduce chemical costs
- Reduce water usage
- Improve safety
- Improve performance and materials protection
- Improved utilization of plant staff
- Improve diagnostics and troubleshooting
- Achieve peace of mind

One aspect in this regard, which is valuable for any program, has been the development of traced chemistry programs, which allow solid state sensors to accurately measure chemical concentrations in the circulating cooling water without the need for reagents, or even a laboratory. Also, the instrumentation that is available for monitoring standard operating parameters has improved greatly in recent years, allowing for accurate, continuous, online readings of critical data, including the following:

- pH
- Specific conductivity
- Oxidation-reduction potential (ORP) for controlling oxidizing biocides
- Corrosion rate
- Scaling potential
- Biofouling potential
- Chemical feed tank levels

The unit shown in Figure 12 contains the instruments needed to accurately monitor and control important aspects of cooling water chemistry. It includes corrosion coupons, sensors, flow regulators and

FIGURE 9. Shown here is a carbon steel corrosion test specimen using a polyphosphate water-treatment program

FIGURE 10. This carbon steel corrosion test specimen after converstion to RPSI inhibitor

other related hardware. The analytical data can be distributed both internally and remotely to assist both plant personnel and external experts with evaluation of system conditions. Many new plants nowadays, at least in the power industry, are minimally staffed, with few, if any, personnel who are rigorously trained in cooling system chemistry.

Against this backdrop, a digital data feed that allows outside consultants to monitor system conditions can be quite valuable for maintaining system reliability. Further, ever since Langelier produced his pivotal calcium carbonate scale calculations in the 1930s [*3*], increasingly accurate and comprehensive computer models have been developed to evaluate the scale and corrosion potential for untreated water, and to calculate the proper chemistry, strength and cost of products needed to control scale and corrosion issues. Modeling programs are available for purchase from independent software companies and are also offered by water-treatment service providers, often included with the water treatment chemistry. The best programs are capable of selecting and evaluating the most appropriate and cost-effective treatment programs that meet the plant's environmental and operating constraints, such as water quality, alternate water sources, and costs for chemicals, water and sewer.

A key aspect with any program is the input of accurate historical chemical analyses of the raw water feed to the system. Both authors have seen over and over again project specifications that have only partial raw-water data — often sampling that is based on just a snapshot in time. Many owners and owner's engineers do not understand that comprehensive water-quality data are es-

FIGURE 11. After the fouling was removed from this plate-and-frame heat exchanger, it remained clean using subsequent water treatment with non-P chemistry

sential, not only for selecting proper chemical-treatment methods, but to ensure the proper selection and sizing of water-treatment components such as clarifiers, filters, reverse osmosis units and other equipment.

Closing thoughts

Chemical-treatment programs for cooling towers have undergone significant evolution over the last several decades. New chemistry formulations and improved instrumentation and control options are making these programs even more effective. A key challenge is microbiological control (which is beyond the scope of this article). The benefits of well-applied scale/corrosion control programs can be quickly undermined if microorganisms are allowed to settle and develop colonies within cooling systems. Microbes thrive in warm and wet environments, and even slight lapses in treatment efficiency may result in big problems.■

Edited by Suzanne Shelley

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FIGURE 12. This compact cooling-water monitoring unit contains all of the sensors required to monitor, calculate, control, and communicate the key aspects of the cooling-water chemistry, ensuring proper operation

chemistry, water treatment, air-quality control, and related engineering positions at City Water, Light & Power (Springfield, Illinois) and Kansas City Power & Light at the company's La Cygne, Kansas, station. His experience also includes 11 years at two engineering firms. Buecker spent two years away from the power industry as acting water/wastewater supervisor at a chemical plant. He has authored many articles and three books on power plant water and steam chemistry and air-pollution-control topics. He is a graduate of Iowa State University, with additional course work in fluid mechanics, material and energy balances, and advanced inorganic chemistry. He is a member of the American Chemical Society, American Institute of Chemical Engineers, American Society of Mechanical Engineers, Cooling Technology Institute (corporately), and the National Association of Corrosion Engineers. Buecker is on the planning committees for the annual Electric Utility Chemistry Workshop and Power-Gen International, and he serves on the Advisory Council for the annual International Water Conference.

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Particle Size Characterization and Analysis

Several methods and calculations are available for determining particle size and particle-size distribution. This article provides and overview on how to use them

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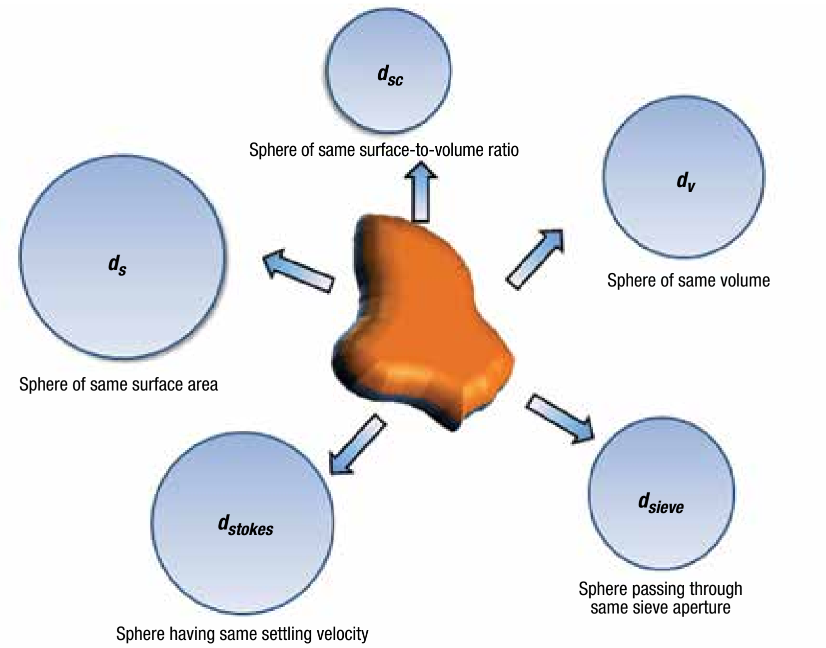


FIGURE 1. Equivalent spherical diameters based on different controlling characteristics can result in different particle size values for the same particle

The behavior of particulate material is greatly dependent on its geometric properties, including particle size, shape and particle-size distribution (PSD). In industrial processes, these parameters affect phenomena such as sedimentation, flow through porous media, fluidization, gas-solid separation by cyclone, size enlargement (agglomeration) and powder mixing. Specific examples of particle-size effects include the following:

- Particle size affects the permeability of packed beds
- Stokes's diameter is important to free settling of particles in fluid
- The efficiency of gas-particle separation devices is strongly dependent on the particle size and PSD
- The fluidization behavior of particles depends strongly on particle size and relative density
- Solids mixing and segregation is also dependent on the particle size of solid ingredients

Similarly, particle size affects the end-use properties of many particulate products, such as the reactivity of catalysts, bioactivity and dissolution of drugs, setting time of cement, hiding power of cement, flowability of powder, and packing density of advanced materials. Particle properties also play a central role in the handling of solids-containing fluids.

Unfortunately, particle size characterization is among the most neglected areas in the field of chemical engineering, despite its importance in the vast majority of unit operations involving particulate matter and bulk solids handling. Since particle size measurement is routinely employed in many industries, appropriate techniques for particle measurement, and data presentation and interpretation, are of utmost importance to understand solids behavior, handling and final product qualities.

The measurement and selection of appropriate mean (average) particle size is a difficult task because of inherent particle characteristics. The difficulty is further compounded by the availability of a wide range of measurement techniques, which report different types of mean particle size and particle size distributions. The main objectives of this article are to address the following issues of particle characterization:

- What are the ways that the size of single particle can be described?
- What are the ways that the size of an assembly or population of particles can be described?
- How are different types of mean particle size calculated and selected from a given PSD?
- How are particle size distributions based on different quantities represented?
- How can engineers convert a PSD based on one quantity to another?

Describing single-particle size

Representing the size of a particle by its diameter is common, because the use of a single linear dimension to represent particle size is desirable for simplicity. Spherical particles can be conveniently defined by a single dimension (diameter). However, major issues arise for irregularly shaped particles, which is the case for most real-world applications.

There are several measures available to represent particle size, categorized into three areas (Figure 1, Table 1 and Ref. 1), as shown here:

(1) Equivalent spherical diameter
(2) Equivalent circle diameter
(3) Statistical diameters

Equivalent-spherical-diameter methods determine diameters by measuring a size-dependent property of the particle and relating it to a single linear dimension [2]. The equivalent sphere diameter takes advantage of the ideal shape of a sphere represented by the single dimension. The equivalent spherical diameter is the diameter of a sphere that shows

the same controlling characteristics as the particle under investigation. The controlling characteristics could be volume, surface area, surface-area-to-volume ratio, settling velocity or other characteristics, as mentioned in Table 1, and Equation (1), which uses volume as the controlling characteristic. The equivalent volume sphere diameter (d_V) equals the diameter of a sphere with the same volume as the particle (V_P).

$$V_P = \pi/6 \; d^3_V \quad (1)$$

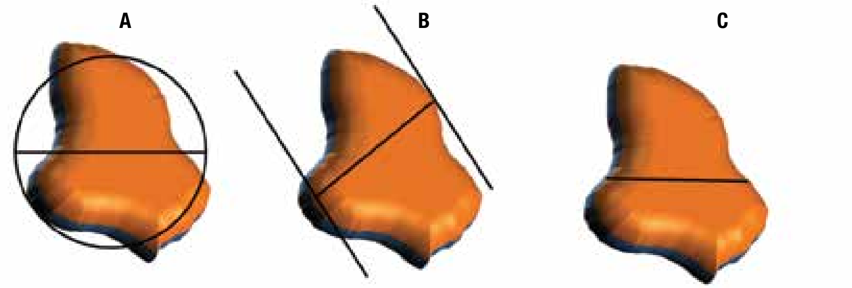
Hence, volume-equivalent sphere diameter is given by Equation (2).

$$d_V = \sqrt[3]{\frac{6 V_P}{\pi}} \quad (2)$$

Several commonly used equivalent-sphere diameters are shown in Table 1 and Figure 1. More definitions can be found from Allen [2]. Microscopy is widely used to measure the particle size based on length.

The commonly used statistical diameters are: Feret's diameter and Martin's diameter. Feret's diameter is defined as the distance between two parallel tangents, while Martin's diameter is defined as a length of the chord that bisects the particle outline (Figure 2).

Equivalent circle diameters, such as the projected area diameter (area of circle with the same area as the projected area of the particle under investigation), can also be used as shown in Figure 2A. These measures are outdated due to their statistical nature and poor reproducibility because there are many possibilities to estimate distance between tangents and bisector.



Circle with same projected are as particle — Parallel tangents Feret's diameter — Line bisecting projected are of particle Martin's diameter

FIGURE 2. Martin's diameter and Feret's diameter are two types of statistical diameter from microscopy

Size of an assembly of particles

Description of the mean (average) size of a population of particles is very challenging. It is advantageous to know the PSD of the solid products to establish the relationship between particle size and product performance. However, a single value for the mean particle size is often required for quality control and product comparison purposes. Hence, mean particle size is normally calculated from the given PSD. The average particle size represents the central tendency of PSD. The common measures of particle size for a given PSD are mean, mode and median (Figure 3). Mean size can be defined in different ways, including arithmetic mean, quadratic mean and Sauter mean. The mode (x_{mode}) is the most commonly occurring size within the particle population and represents the peak of given PSD. The median size ($x_{50\%}$) represents particle size at 50% cumulative frequency.

The mean size for the particle population under consideration can be specified in different ways. The common way of defining the mean size is arithmetic mean (Equation 3).

$$D[1,0] = \frac{\sum_{i=1}^{n} x_i}{\sum_{i=1}^{n} n_i} \quad (3)$$

Mathematically, it is represented as D[1,0], since the power of the diameter term in the numerator is 1 and that in the denominator is 0 ($x_i^0 = 1$). It is generally advisable to use some kind of weighted mean size to evaluate the effects of particle size on the product quality or performance. For example, weighting of size by surface area is more meaningful for particles where surface area plays significant role (as in the case of catalysts). Equation (4) shows the arithmetic mean weighted by number of particles.

$$D[1,0] = \frac{\sum_{i=1}^{n} x_i n_i}{\sum_{i=1}^{n} n_i} \quad (4)$$

It is also possible to calculate mean based on the surface area and volume (Equation (5)):

$$D[2,0] = \frac{\sum_{i=1}^{n} n_i x_i^2}{\sum_{i=1}^{n} n_i}, \qquad D[3,0] = \frac{\sum_{i=1}^{n} n_i x_i^3}{\sum_{i=1}^{n} n_i} \quad (5)$$

The biggest drawback of these formulas is the requirement to calculate a number of particles, which is challenging and difficult task for real applications. However, this issue can be addressed by relating the number to an easily measurable quantity. One probable solution is to relate the number of particles to the mass in the given size interval [3, 4]. The number of particles to the mass in the given size interval can be related as follows:

$$n_i = \frac{6 M_i}{\pi \rho_s x_i^3} \quad (6)$$

Where n_i is the number of particles in the i^{th} size class, M_i is the mass of the particles in the i^{th} size class, and ρ_S is the solid density or particle density. If you substitute Equation (6) into Equation (4), and divide the resulting equation by the total weight of particles (M_t), the final equation is shown in Equation (7), since mass fraction in a given size interval is $m_i = M_i/M_t$.

$$D_{1,0} = \left(\frac{\sum_{i=1}^{n} \frac{m_i}{x_i^2}}{\sum_{i=1}^{n} \frac{m_i}{x_i^3}} \right) \quad (7)$$

Similarly, we can obtain $D[2,0]$ and $D[3,0]$ as follows:

$$D_{2,0} = \left(\frac{\sum_{i=1}^{n} \frac{m_i}{x_i}}{\sum_{i=1}^{n} \frac{m_i}{x_i^3}} \right)^{1/2} \text{ and } D_{3,0} = \left(\frac{1}{\sum_{i=1}^{n} \frac{m_i}{x_i^3}} \right)^{1/3} \quad (8)$$

The widely used mean size is the surface moment mean (also known as Sauter's mean).

$$D_{3,2} = x_{SV} = \left(\frac{\sum_{i=1}^{n} n_i x_i^3}{\sum_{i=1}^{n} n_i x_i^2} \right) \quad (9)$$

This can be changed in terms of mass fraction using Equation (6) and Equa-

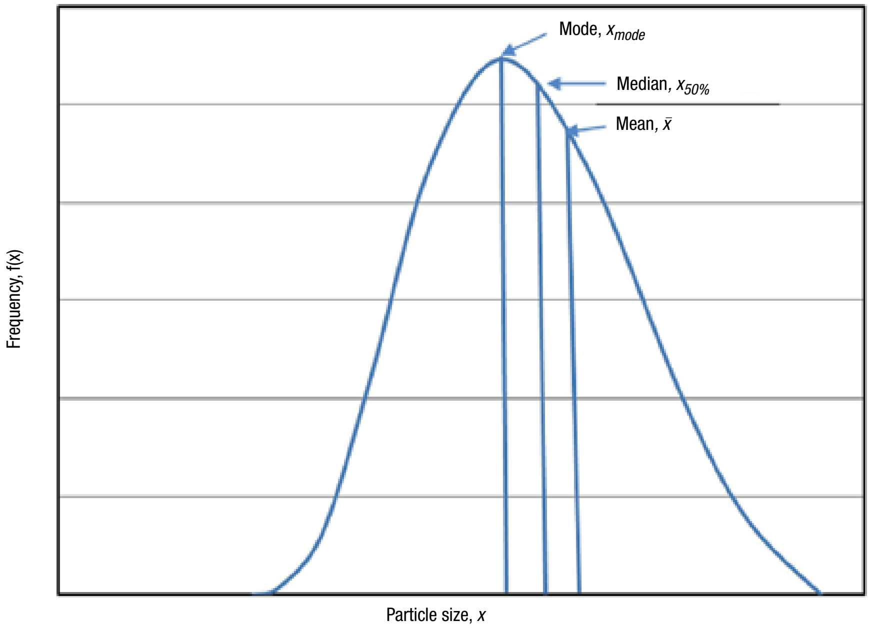


FIGURE 3. The graph shows representations of mean, median and mode of the particle size distribution

tion (9), as shown in Equation (10):

$$D_{3,2} = x_{SV} = \left(\frac{1}{\sum_{i=1}^{n} \frac{m_i}{x_i}}\right) \quad \textbf{(10)}$$

The volume moment mean size in Equation (11) is also widely used in chemical engineering. This is also known as DeBroucker's mean size.

$$D_{4,3} = \left(\frac{\sum_{i=1}^{n} n_i x_i^4}{\sum_{i=1}^{n} n_i x_i^3}\right) \quad \textbf{(11)}$$

Ambiguity can arise when different mean sizes are used. Consider the population of particles containing 10 particles (4 particles of size 1 mm, 3 particles of size 1.5 mm, 3 particles of size 2 mm). We have many choices and can calculate different types of the mean sizes for the same population. It is clear that multiple answers are possible, as shown below for the same population:

D[1,0] = 1.45 mm, D[2,0] = 1.51 mm, D[3,0] = 1.56 mm, D[3,2] = 1.675 mm. All of these are technically correct; the goal should be to select the most suitable value, which is dictated by the end application. For catalyst particles, for example, the equivalent diameter based on the surface-area-to-volume ratio is more appropriate (D[3,2]). For pigment particles, projected area diameter (D[2,0]) may be more relevant. The general definition and other aspects of mean particle size have been described in details in Refs. 1 and 5.

Particle size distributions

Almost all solid materials encountered in real applications involve a range of sizes, so it becomes important to determine particle size distribution (PSD), which is essentially a plot of relative quantity versus particle size. PSD is expressed graphically as a density distribution curve or a cumulative distribution curves. The symbol *x* is used here to indicate particle size.

In the general method of data representation for PSD, a fraction of the quantity of particles in each size interval is identified. This quantity can be number, length, surface area, volume or mass.

Mathematical representation of particle size. Mathematically, PSD can be described in terms of density distribution or cumulative distribution. In the cumulative distribution, $Q_r(x)$ gives the relative amount of particles that are smaller than certain size. If the $Q_r(x)$ term can be differentiated, a density distribution $q_r(x)$ is obtained. The two are related by the following differential relationship: $q_r(x) = dQ_r(x)/dx$

The density function, $q_r(x)$, is defined such that $q_r(x)dx$ represents the fraction of the quantity of particles in a size interval from *x* to *x* + *dx*. Thus, *q(x)* is the fractional quantity in a size range from *x* to *x* + *dx*, and $Q_r(x)$ is a fractional or percentage quantity smaller than size *x*. The particle size measurement is based on the different measurement principles.

Different size-analysis instruments employ different principles and report different particle characteristics. These characteristics could be number, length, surface area, volume or mass, which depend upon the principles of measurement of the particle size. This gives rise to PSD values that are based on different quantities, including PSD by number, by length, by surface area, and by volume or mass. The PSD by mass and volume are expected to be same if the particle density is independent of size. The integral relation is given in Equation (12):

$$Q_r(x) = \int_0^{\infty} q_r(x)dx \quad \textbf{(12)}$$

TABLE 1. DEFINITIONS FOR DIFFERENT TYPES OF DIAMETERS (FOR PARTICLE SIZE)

Diameter	Definition	Formula
Surface	Diameter of a sphere (d_s) with the same surface area (S_p) as the particle under investigation	$d_s = \sqrt{\frac{S_P}{\pi}}$
Volume	Diameter of a sphere (d_v) having the same volume (V_p) as the particle under investigation	$d_V = \sqrt[3]{\frac{6\,V_P}{\pi}}$
Surface-volume	Diameter of a sphere (d_{SV}) having the same surface-area-to-volume ratio as the particle under investigation	$d_{SV} = \frac{d_V^3}{d_S^2}$
Stokes	Diameter of a sphere (d_{st}) having the same density and settling velocity as the particle under investigation in laminar flow conditions	$d_{st} = \sqrt{\frac{18\,\mu\,v_t}{(\rho_p - \rho_f)g}}$
Equivalent circle diameter		
Projected area	Diameter of a circle (d_A) having the same projected area (A_p) as the particle under investigation	$d_A = \sqrt{4\frac{A_P}{\pi}}$
Perimeter diameter	Perimeter of a circle with same perimeter as the particle under investigation	$D_{perimeter} = P/2\pi$
Statistical diameter		
Feret's diameter	Distance between two parallel tangents	-
Martin's diameter	Length of line which bisect the given particle outline	-

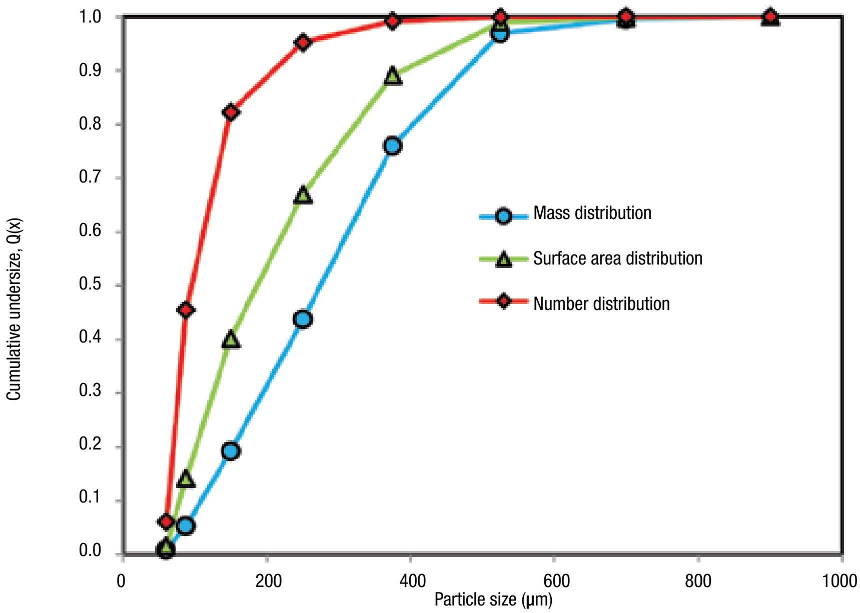


FIGURE 4. Different ways of measuring particle size distribution (using number, surface area and mass) give rise to different curves for cumulative undersize particles

Where the subscript *r* indicates the type of quantity being measured, *q* represents fractional density and *Q* represents cumulative density, as per the International Organization for Standardization (ISO) standard 9276 (Representation of Results of Particle Size Analysis). Thus, the following notations are used to indicate different types of PSDs (Table 2).

Converting among different PSD

Different particle-size analysis instruments measure different types of PSD. For example, microscopy-based techniques generally give number-based distributions, while laser diffraction measures volume-based distributions, and dynamic light scattering (DLS) measures intensity-based distribution. It is often necessary for a given size distribution based on one type of quantity to be converted into other types for comparisons and other operational purposes. For example, one can convert the number-based distribution into a distribution based on mass or surface area. The following relationships are used to relate different types of distributions [1]:

Conversion from number to length: $q_L(x) = k_L q_N(x)$ or $q_1(x) = k_L q_0(x)$ **(13)**

Conversion from number to surface area: $q_S(x) = k_S\, x^2\, q_N(x)$ or $q_2(x) = k_S\, x^2\, q_0(x)$ **(14)**

Conversion from number to mass: $q_M(x) = k_M\, x^3\, q_N(x)$ or $q_3(x) = k_M\, x^3\, q_0(x)$ **(15)**

The values of constants k_L, k_S and, k_M contain information about shape factors, which must be known to make accurate conversions. These factors may vary with particle size and can make it difficult to make accurate conversions. However, the information about the shape factor can be obtained easily, if it is independent of particle size, from the following condition:

$$\int_0^\infty f(x)dx = 1 \qquad \textbf{(16)}$$

The method to determine surface distribution from mass or volume distribution is described below, as in Svarovsky [1] and Rhodes [6].

Converting mass distribution to surface distribution. The method to determine surface distribution from mass distribution is shown below.

TABLE 2. NOTATION FOR DIFFERENT TYPES OF PARTICLE SIZE DISTRIBUTION (ADOPTED FROM REF. 4).

Type of quantity		Measure of quantity	
		Density distribution	Cumulative distribution
Number	$r = 0$	$q_0(x)$	$Q_0(x)$
Length	$r = 1$	$q_1(x)$	$Q_1(x)$
Area	$r = 2$	$q_2(x)$	$Q_2(x)$
Volume	$r = 3$	$q_3(x)$	$Q_3(x)$

Using Equations (14) and (15),

$q_S(x) = k_S\, x^2\, q_N(x)$ and $q_M(x) = k_M\, x^3\, q_N(x)$

$$q_S(x) = k_S/k_M\, (1/x)\, qM(x) \qquad \textbf{(17)}$$

and integrating from 0 to *x*,

$$\int_0^x q_S(x)dx = \frac{k_S}{k_M} \int_0^x \frac{1}{x}\, q_M(x)dx \qquad \textbf{(18)}$$

And from the relation, $q(x) = dQ/dx$

$$\int_0^x dQ_S = \frac{k_S}{k_M} \int_0^x \frac{1}{x} dQ_M \qquad \textbf{(19)}$$

In this way, the surface distribution can be found from Equation (19). The left side of Equation (19) represents the area under the curve (A_T) of 1/*x* versus Q_M, multiplied by the factor k_S/k_M. The factor k_S/k_M, in turn can be found from the normalization condition $\int_0^\infty dQ_S = 1$.

$$\text{Thus, } 1 = (k_S/k_M)A_T \qquad \textbf{(20)}$$

Where A_T is the area under the curve of 1/*x* versus Q_M). Thus, dividing each value of Q_M by A_T should yield the corresponding values of Q_S. Similarly, the method to determine mass distribution ($Q_M(x)$) from number distribution ($Q_N(x)$) is accomplished by multiplying different values of f_n, that correspond to different sizes of *x*, by x^3. The resulting curve of $x^3\, q_N(x)$, is then simply scaled down by a following factor to give $q_M(x)$ [1].

$$k_V = 1/(\int_0^\infty x^3 q_N(x)dx) = 1/A \qquad \textbf{(21)}$$

Example problem

The example problem in this section is solved to illustrate the procedure of converting between different representations of PSD. The PSD data used in the problem are obtained from a sieve analysis.

Example Part A. To convert mass distribution into surface-area distribution, tabulate the values of size interval and mass retained in each interval in columns 1 and 2, respectively in Table 3. Determine the average size, as per equation $[(x_1 + x_2) / 2]$, as shown in column 3.

The mass fraction is calculated by dividing the mass in each interval by the total mass (57.3 g) and tabulate the result in column 4, using the following equation: $m_i/(\Sigma m_i)$.

Then find the cumulative mass

TABLE 3. SIEVE ANALYSIS FOR THE GIVEN PSD										
Screen Interval (µm)	<45	45–75	75–100	100–200	200–300	300–450	450–600	600–800	800–1,000	>1,000
Mass Retained (g)	0	0.5	2.5	8	14	18.5	12	1.5	0.3	0

fraction by adding values cumulatively and tabulate them in column 5. Find out ($1/x$) as in column 6. As explained here, by using Equation (19), we can find the surface distribution:

The integral in the right hand side of the equation represents the area under curve area (A_T) of $1/x$ versus Q_M, which must be calculated. Here, using the trapezoidal rule, we can find out the required value of the integral in Equation (19).

$$\int_0^x dQ_S = \frac{k_S}{k_M} \int_0^x \frac{1}{x} dQ_M \quad (22)$$

The trapezoidal rule to evaluate the integral is shown below. In our case, we must find out the integral value for each of the size intervals, as well as the total ((A_T), as shown below. The calculated values have been tabulated in column 7 of Table 3.

$$\int_{x_1}^{x_n} f(x)dx \cong \frac{1}{2}\sum_{i=1}^{n}(x_{i+1} - x_i)(f_{i+1} + f_i) \quad (23)$$

For example, the first and second entries in column 7 are

$= 0.5(0.009-0)\ ((1.667+0)\ x10^{-2}) = 0.075 \times 10^{-3}$

$= 0.5(0.053-0.009)\ ((1.143+1.667)\ x10^{-2}) = 6.18\ x\ 10^{-4}$

The sum of all the entries in the Column 7 gives the value of $1/k_S/k_M = 0.004859$, as per Equation (20).

Next, calculate the cumulative area under the curve, as shown in Column 8 of Table 3.

Finally, multiply each entry in column 8 by (k_S/k_M) to yield the surface distribution, as per Equation (19).

$0.075 \times (1/0.004859) = 0.015$, also $0.688 \times (1/0.004859) = 0.0142$

This will result in a cumulative surface distribution, as shown in Column 9.

Example Part B. To convert mass distribution into number distribution, a similar procedure is employed, as the two are related by the following relationship, $q_M(x) = k_M\, x^3\, q_N(x)$.

Integrating from 0 to x,

$\int_0^x q_N\ (x)\ dx\ = 1/k_M \int_0^x 1/x^3\ q_M\ (x)dx$

And from the relation, $q(x) = d_Q/dx$

$\int_0^x dQ_N\ = 1/k_M \int_0^x 1/x^3\ dQ_M$

In this way, we can find the number distribution from the mass distribution. The integral can be estimated using the trapezoidal rule, as follows. The remaining steps are similar as illustrated in the case of the solution for Part A. The calculated values can be found in Table 4.

$$\int_0^x \frac{1}{x^3} dQ_M \cong \frac{1}{2}\sum_{i=1}^{n}(Q_{M,i+1} - Q_{M,i})\left(\frac{1}{x_{i+1}^3} + \frac{1}{x_i^3}\right) = A_T \quad (25)$$

TABLE 4. CONVERSION OF GIVEN SIEVE DATA BASED ON MASS DISTRIBUTION INTO SURFACE AREA BASED SIZE DISTRIBUTION								
1	2	3	4	5	6	7	8	9
Sieve Interval	Mass retained (m_i)	Average Size (x)	Mass fraction $dQ_M = q_m dx$	Cumulative mass distribution, Q_M	$(1/x) \times 10^{-2}$	Area under curve $(1/x$ vs. $Q_M) \times 10^4$	Cumulative area under curve $(1/x$ vs. $Q_M) \times 10^3$	Cumulative surface distribution, Q_S
<45	0			0	0	0	0	0
45–75	0.5	60.0	0.009	0.009	1.667	0.75	0.075	0.015
75–100	2.5	87.5	0.044	0.053	1.143	6.18	0.688	0.142
100–200	8.0	150.0	0.140	0.192	0.667	12.632	1.951	0.402
200–300	14.0	250.0	0.244	0.437	0.4	13.031	3.254	0.670
300–450	18.5	375.0	0.323	0.759	0.267	10.762	4.33	0.891
450–600	12.0	525.0	0.209	0.969	0.19	4.787	4.809	0.990
600–800	1.5	700.0	0.026	0.995	0.143	0.436	4.853	0.999
800–1,000	0.3	900.0	0.005	1.000	0.111	0.066	4.859	1.000
>1,000	0	0	0.000	0.000	0	0	0	0
	Total Mass = 57.3					Total of Column 7 = k_S/k_M = 0.004859		

Example Part C. This example illustrates how to calculate different types of mean sizes. Calculation of mean sizes, such as D[1,0], D[2,0], D[3,0] and D[3,2], are shown for the same dataset in Table 5.

$$D_{1,0} = \left(\frac{\sum_{i=1}^{n} \frac{m_i}{x_i^2}}{\sum_{i=1}^{n} \frac{m_i}{x_i^3}} \right) = \frac{2.1353 \times 10^{-5}}{1.7018 \times 10^{-7}} = 125.5 \ \mu m \quad (26)$$

Similarly, using Equations (8) and (9), D[2,0] and D[3,0] can be calculated as follows:

$$D_{2,0} = \left(\frac{\sum_{i=1}^{n} \frac{m_i}{x_i}}{\sum_{i=1}^{n} \frac{m_i}{x_i^3}} \right)^{1/2} = 150.5 \ \mu m \quad (27)$$

$$D_{3,0} = \left(\frac{1}{\sum_{i=1}^{n} \frac{m_i}{x_i^3}} \right)^{1/3} = 180.4 \ \mu m \quad (28)$$

Finally, the Sauter mean can also be calculated from Equation (10).

$$D_{3,2} = (1/(\textstyle\sum_{i=1}^{n} (m_i/x_i)) = 259.4 \ \mu m \quad (29)$$

Thus, the same population of particles yield different results depending upon the type of mean required. The plot of the cumulative undersize distribution based on the mass, surface area and number on the same plot is shown in Figure 4. Care must be taken to account for the errors inherent in this type of conversion in the final estimation [*5*].

In most applications in solid-fluid separation, the PSD by mass is of most value, since we are mostly interested in gravimetric efficiencies and mass balances. The PSD by surface or by number may be more relevant in some cases of liquid clarification, where turbidity is an important parameter [*1*].

TABLE 5. CONVERSION OF GIVEN SIEVE DATA BASED ON MASS DISTRIBUTION INTO NUMBER-BASED PARTICLE SIZE DISTRIBUTION				
1	2	3	4	5
Cumulative mass distribution, Q_M	$(1/x^3) \times 10^6$	Area under curve $(1/x^3$ vs. $Q_M)$ auc $\times 10^8$	Cumulative area under curve $(1/x^3$ vs. $Q_M)$ cauc $\times 10^7$	Cumulative Number distribution Q_N
0	0	0	0	0
0.009	4.63	2.08	0.208	0.0614
0.053	1.49	13.4	1.54	0.4547
0.192	0.296	12.5	2.79	0.8225
0.437	0.064	4.4	3.23	0.9522
0.759	0.019	1.34	3.37	0.9916
0.969	0.00691	0.271	3.39	0.9996
0.995	0.00292	0.0129	3.4	1.0000
1.000	0.00137	0.00112	3.4	1.0000
		Total of column = $1/k_M$ = 3.39537 E-07		

When converting from one type of distribution to another, it is suggested that a method be used that gives a suitable PSD to avoid errors inherent in such conversion calculations. The selection of a method should be based on both the particle size and the type of distribution required. ■

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Economic Indicators

2017 2018 2019

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CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957–59 = 100)	Apr. '19 Prelim.	Mar. '19 Final	Apr. '18 Final
CE Index	617.3	616.0	595.0
Equipment	754.4	752.8	723.5
Heat exchangers & tanks	670.7	668.4	637.5
Process machinery	731.3	728.2	708.8
Pipe, valves & fittings	976.7	977.7	952.3
Process instruments	419.8	421.2	419.2
Pumps & compressors	1068.4	1066.0	1015.6
Electrical equipment	556.1	557.5	533.2
Structural supports & misc.	834.0	827.7	776.0
Construction labor	335.9	334.5	331.6
Buildings	598.3	599.8	586.4
Engineering & supervision	316.9	316.9	310.4

Annual Index:

2011 = 585.7

2012 = 584.6

2013 = 567.3

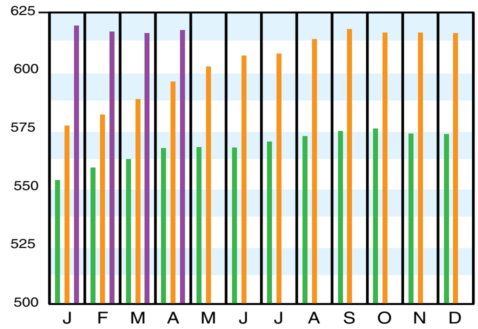
2014 = 576.1

2015 = 556.8

2016 = 541.7

2017 = 567.5

2018 = 603.1

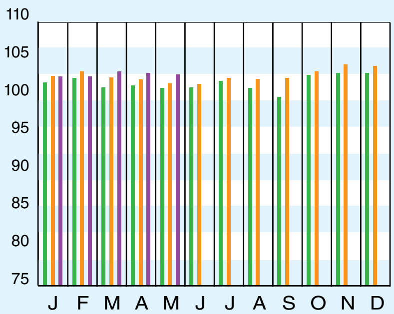


Starting in April 2007, several data series for labor and compressors were converted to accommodate series IDs discontinued by the U.S. Bureau of Labor Statistics (BLS). Starting in March 2018, the data series for chemical industry special machinery was replaced because the series was discontinued by BLS (see *Chem. Eng.*, April 2018, p. 76–77.)

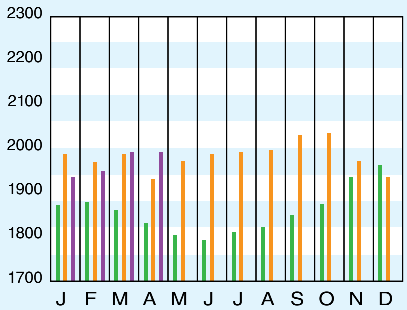
CURRENT BUSINESS INDICATORS

CURRENT BUSINESS INDICATORS	LATEST	PREVIOUS		YEAR AGO
CPI output index (2012 = 100)	May '19 = 103.0	Apr. '19 = 102.8	Mar. '19 = 102.8	May '18 = 102.9
CPI value of output, $ billions	Apr. '19 = 1,994.3	Mar. '19 = 1,984.7	Feb. '19 = 1,953.0	Apr. '18 = 1,937.1
CPI operating rate, %	May '19 = 77.1	Apr. '19 = 77.0	Mar. '19 = 77.1	May '18 = 77.6
Producer prices, industrial chemicals (1982 = 100)	May '19 = 257.4	Apr. '19 = 255.9	Mar. '19 = 257.9	May '18 = 270.9
Industrial Production in Manufacturing (2012 =100)*	May '19 = 104.8	Apr. '19 = 104.6	Mar. '19 = 105.1	May '18 = 104.1
Hourly earnings index, chemical & allied products (1992 = 100)	May '19 = 184.7	Apr. '19 = 185.0	Mar. '19 = 184.1	May '18 = 184.0
Productivity index, chemicals & allied products (1992 = 100)	May '19 = 96.2	Apr. '19 = 96.6	Mar. '19 = 95.7	May '18 = 97.8

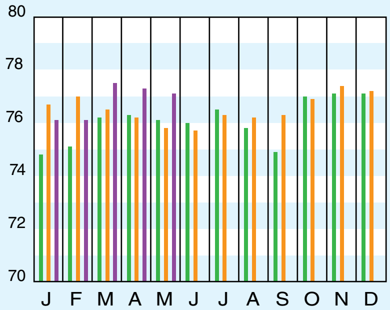
CPI OUTPUT INDEX (2000 = 100)†



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



*Due to discontinuance, the Index of Industrial Activity has been replaced by the Industrial Production in Manufacturing index from the U.S. Federal Reserve Board.
†For the current month's CPI output index values, the base year was changed from 2000 to 2012
Current business indicators provided by Global Insight, Inc., Lexington, Mass.

CURRENT TRENDS

The preliminary value for the *CE* Plant Cost Index (CEPCI; top; the most recent available) for April 2019 increased from the previous month's value, reversing two months of small declines. The increase in April for the overall CEPCI is a result of growth in the Equipment and Construction Labor subindices. The increase in those offset a small decline in the Buildings subindex. The Engineering & Supervision subindex remained unchanged from the previous month. The overall CEPCI preliminary value for April 2019 stands at 3.7% higher than the corresponding value from a year ago. Meanwhile, the CBI numbers for May 2019 (middle) show small increases in the CPI Output Index, CPI operating rate and Producer Prices.